RM-78-46

ENERGY ANALYSIS:

Its Utility and Limits

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September 1978

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PREFACE

One of the central tasks of the Energy Systems Program at IIASA is to set up a basic logic for forecasting the level and the structure of energy consumption. For the second objective, efficient techniques are already at hand, through the use of the market penetration concept permitting an analysis of all levels of the energy chains from primary sources to final consumption, and the effort is now concentrated on providing a convincing theorization.

For the first objective, on the contrary, the situation is still fluid. Many modeling efforts have been made, at IIASA too, but their contradictory results and their dependence on soft assumptions calls for a more refined understanding of the systems. Any tool that may help perceiving its internal mechanisms, possibly leading to the determination of energy demand, is welcome.

In this light, the new discipline of energy analysis appears a very ubiquitous and penetrating device, which helps visualizing the intricate relationships between energy and technical and economic factors, their limits, and their evolution in time. In this memorandum, some attempt is made to quantify these relationships, and this may be a first step to the definition of the invariants sought.

We have invited Dr. Malcolm Slesser to prepare this review for IIASA to contribute to the understanding of the relationships between energy and the economy.

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ABSTRACT

Energy analysis - the analysis of the energy "content" of goods and services - in the sense of considering economic issues in energy terms, is a comparatively recent development. While the conventions of accounting in energy terms are broadly agreed by workers in the field, the question of economic interpretation is still a matter for dispute. Energy analysis throws light upon how energy enters the economic process, and can therefore usefully supplement economic analysis. For example, while the minimum energy requirement for a transformation process is set by thermodynamic considerations, little is known how these relate to production in a finite time world. It is shown that money can be treated as the derivative of two fundamental resources, energy and labour and that energy analysis is not an energy theory of value. Energy should not be treated simply as heat, but as providing both negentropy and heat. Accounting in energy terms does involve a loss of information over that of money accounting with respect to current activities, but may provide more precise statements about future costs.

ACKNOWLEDGEMENTS

The author would like to take the opportunity of thanking Professor Häfele for the opportunity to spend some time at IIASA to put together these thoughts on energy analysis.

I also acknowledge with pleasure the assistance of many members of the Energy Studies Unit, Strathclyde University, for information supplied.

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A Moment white, then gone forever"

Robert Burns

1. Introduction

1.1 Introduction

Energy analysis (EA) has been defined as the estimation of the amount of primary energy resource sequestered in order to deliver a given good or service to a chosen point in the economic system /1/. In this sense it appears entirely analogous to money, but this is not really so. Money embraces all the factors of production, many of which have a cost based upon an interaction of supply and demand as well as profit and rent, and so on. Energy analysis reflects only energy used up and reflects this "cost" not in money units, but in energy units.

Just as there is a world of difference between accountancy and economics, so there is a distinction between accounting for production in energy terms, and utilising the numbers to explain behaviour or test hypotheses. Energy analysis proponents have developed reasonably satisfactory methods of accounting for energy, but are only just beginning to use the data for interpretation. This paper is about the present state of the art, and where it might lead.

As an illustration let us take the case of ammonia manufacture. It was first synthesised in 1912 by an electric-arc process in Norway, and with changing technology and economies of scale both relative price and the energy requirements for production have dropped. The price plot in constant prices (see Figure 1 in Section 3) resembles the energy requirement plot (see Figure 3 in Section 3). Today the price is rising. But cost is not price. The energy requirement has evened out and so has the cost. There are good reasons for both. Energy analysts believe that behaviour of the energy plot could have served to predict the behaviour of the economic plot, that is to say that the relative price of ammonia cannot be expected to fall further, and real prices will closely reflect current trends in energy prices.

Appendix 2 carries a simple energy analysis calculation for those unfamiliar with the methodology.

The utility of energy analysis has been severely criticised by many economists /2,3,4/ who argue along two main lines: at best it cannot provide as meaningful a policy analysis as can economic analysis, and at worst it is a single-parameter theory of value. Even T. Koopmans, who has given some time to a study of energy analysis /5/, concluded that its obsession with energy obscured the fact that in the real world we are just as much concerned with other scarce resources like land, water, or copper.

In fairness to energy analysis it must be said that most critics have misunderstood its objectives. Partly this is due to a vocal group of environmentally concerned people who have propagated an energy theory value /6,8/, of whom the best known is perhaps H. Odum /7/. Energy theories of value are odious to economists. Partly this arises out of an instinct in the economics profession to protect its intellectual domain, whereas EA actually seeks to supplement, not supplant, economic analysis. But principally misunderstanding arises around the role energy is thought to play in the economy. To the economist energy is a resource to be treated like any other resource. To the energy analyst energy has a unique quality. It is the only one of man's endowed resources apart from time that cannot be recycled. Moreover there is no susbstitute for energy. Therefore it can be considered a key factor in allocation decisions. However, scarcity of energy plays no part in the theoretical construct of EA, though the conditions of 1974 to 1976 have undoubtedly given it a boost.

Readers unfamiliar with the philosophical background of EA may like to read the short allegorical story in Appendix 1.

1.2 Energy

Like any specialist word that enters everyday conversation, the word energy has become somewhat ambiguous. Energy is a concept invented by scientists to account for the fact that when heat or work are put into a taken out of a system, and that system ends up in a different state than its original, some property of the system has to account for the difference. This property is called energy content and thermodynamicists argue that it is an inherent property of the system. Without this useful definition it would be quite impossible to deal with the fact that heat and work are interchangeable.

For the non-energy specialist, already two difficult concepts have been introduced: heat and work. Both are measured in the same dimensions, both are forms of energy, but play quite different roles in our economy. The kerosene in a jet engine does work in pushing the jet aeroplane through sky and leaves behind a trail of heat. The kerosene in a green-house heater provides background warmth, but produces no work. The change of heat into work requires the increase in entropy of the system, that is to say, a running down of the system. For the non-thermodynamicist this idea of running down our system through an <u>increase</u> in entropy is conceptually irritating, and many like to reverse the order, and describe the system as one which uses up negentropy. The first law of thermodynamics state that heat is neigher lost nor gained. The second law defines the manner in which negentropy is consumed when a non-spontaneous process occurs, such as turning heat into work.

Strictly speaking then we can never have an energy crisis; but we could and may have a negentropy shortfall.

The statement that there is no substitute for energy, though true, is not the nub of the matter, since energy is abundant and is conserved. Correctly the statement should be 'there is no substitute for negentropy', It is as R. Burns /48/ said "<u>Like the snowflake in the river, A moment white, then gone forever</u>".

1.3 Historical Perspective

In 1881 Lord Kelvin, professor of mechanical engineering at Glasgow University, published his analysis of the optimum cross section of an electrical conductor /9/ using a methodology akin to present-day energy analysis. In the early 1920s F. Soddy, Nobel laureate in chemistry, became obsessed with the fact that in England there was poverty and unemployment, yet there existed abundant energy. He saw energy as the driving force of the economy /10/. Soddy was to lose his reputation as a scientist as a result of his obsession with energy and the economy, and though his books sold well, few agreed with him. It was his fate to be making his arguments just at the time that J.M. Keynes, with whom he violently disagreed, was having such an impact on economic thought in England. Not unnaturally it was the thermodynamicists who tended to return to the role of energy, if only through the concept of entropy, as did G.K. Lewis and W. Ehrenfest. In 1949 H.B. Chenery /11/, an economist, published an article, with numbers, arguing that energy should be introduced into the Cobb-Douglas production function. Nothing seems to have come from this suggestion, but Chenery did not lose his reputation. He became vice-president of the World Bank.

In 1971 H. Odum published his remarkable book, Power, Environment and Society /7/. Odum argued that money and energy went in opposite directions in the economy, and he virtually proposed an energy theory of value. His book, providing many factual examples, gave ecologists and environmentalists considerable ammunition in their fight against unnatural industrialisation. Odum was instrumental in having Public Law, 93-577 passed in Congress, which required a net energy analysis to be carried out before funding any major R & D proposal in the energy field. Only later did it become apparent that there was no consensus upon how net energy might be defined /12/.

Odum's energy analysis looked at whole systems, and contained fairly rough numbers. The first hard analysis of any magnitude appeared in 1973, when S. Berry, a physical chemist from Chicago, and a graduate student, M. Fells, published their energy analysis of an automobile production system, starting fron ores in the ground and finishing with a bright shining new automobile /13/. Their major contribution was not only to trace the actual energy flow, but to estimate the theoretical free energy (ΔG) needed to carry out the various processes. Thus they were able to show that it took some five times the theoretical energy to transform ores into a real car. This allowed Berry to make some interesting philosophical points of which the following is perhaps the most important:

> "If the economists in the market place were to determine their shortages by looking further and further into the future, these estimates would come closer and closer to the estimates made by their colleagues, the thermodynamists".

While Berry was exploring the dimension of waste, M. Slesser had been examining the energy requirement to make protein in a wide variety of systems, both agricultural and industrial, and found a surprising correlation between output intensity (kg protein per hectare year) and

and the input intensity (all the inputs, expressed as energy needed to furnish them) in energy per hectare year /14/. Subsequent work has substantiated this correlation /16/, and it may be interpreted as a land-energy trade-off, with diminishing returns to intensification, i.e. the price of intensification is more energy use/unit of product.

The decision by OPEC to raise the price of oil in 1973 gave a huge stimulus to the subject of energy, and interest in energy analysis burgeoned. Thus the publication by B. Hannon and R. Herendeen /15/ of their energy-based input output table of the US economy in 1963, started several years before, drew enormous interest. For the first time one could readily compute for whole industries the average energy resource needed to furnish a given class of good either to an intermediate point in the economy or to final demand. Since then a 1968 version has been issued, and other groups have tackled the severe problem of disentangling energy sold at various prices within the economy with a view to producing more exact tables. This approach provides only historical average energy intensity, not marginal values.

By early 1974 many production costs were being couched in energy terms. Some people were quick to seize upon any numbers that showed nuclear energy in a bad light, and as a result some bad numbers got into circulation, and remained there. There was no consistent basis for making calculations, and no way of checking the truth of various statements, except by repeating the analyses oneself. At this point the International Federation of Institutes of Advanced Study (IFIAS) stepped in to arrange a workshop to establish the conventions and methodology of what was then often called Energy Accounting.

Twenty-four people known to have involvement in the topic were invited to a remote country house in Sweden for one week. They came from industry, the universities, business, and government, and embraced nine nationalities. Over 4000 copies of the workshop report /1/ have been sold and the conventions proposed have been widely accepted.

Two activities have succeeded that workshop. In 1975 a second workshop /17/ was held at which some dozen energy analysts met with a dozen economists, including L. Klein and T. Koopmans, to consider what role energy analysis could play in economic analysis. Some fragile bridges were built between the physical scientists and technologists on the one hand, and the economists on the other. The concept of limits to technological progress through the use or understanding of the second law of thermodynamics was passed from the scientists to the economists, while the economists demonstrated their involvement with a system much more complex than a purely physical system, and showed that deterministic methods could not forecast the behaviour of an economic system. It became very clear that economics was, at least in part, a behavioural science. It had not yet developed ways of considering constraints imposed by thermodynamic considerations. So far we have not seen energy analysis being embraced with any enthusiasm by the economics community, not even by those who were present at that workshop. Energy analysts, on the other hand, are convinced that a total systems approach, coupled to economics, is essential to a proper understanding of the economic system and its development.

The work of developing better methods and conventions seems to have fallen to the CCMS (Committee on Challenges Facing Modern Society) of NATO which now meets intermittently to discuss energy analysis matters. A sizable man-power is now devoted to establishing the energy content of goods and services, though little theoretical development on the role of energy in the economy has emerged. Energy analysis is certaintly being used to verify the (energy) validity of various economic and other scenarios, but there is no report yet of its actual use as a tool for policy making. This should not surprise us. Those who might be influenced neither understand nor are trained to analyse what energy analysis has to say. No-one has yet made a historical study to show that an energy analysis, had it been carried out, might have resulted in a better anticipation or a better decision.

The state of the art is that a growing body of data is being generated, and there is now scope for the use of this data in testing hypotheses of the role energy plays in the economy.

2. Definition

2.1 Conventions

2.1.1 Energy Terminology

Because energy analysis seeks to determine the energy resource required to make a given good or service available to the economy, a convention has arisen in which that amount of energy is referred to as a 'requirement'. In some publications one may come across the words 'energy cost'. In the conventions of energy analysis one does not use the word 'cost' unless one is applying it to the money price of energy. However some people do use the words 'energy cost' to imply 'energy requirement'.

For example, an early publication by P. Chapman, M. Slesser, and G. Leach /18/ is entitled The Energy Cost of Fuels". This choice of title was due as much to editorial pressure as to wilful action by the authors.

In general in this paper 'energy requirement' will be the 'Gross Energy Requirement' (GER) as defined in the IFIAS convention /1/. 'Energy cost' will refer to units of money per physical unit of energy, and 'energy intensity' will refer to units of energy per unit of money (MJ/£, MJ/A$, etc.).

2.1.2 Labour

All energy inputs to the production of goods and services finishes up as final demand by the consumers, who in turn provide the labour.

Let G be the total energy entering the national system per year, and let there be n workers. Then the average energy consumption per worker is G/n. If y be the GER for a certain good, which requires the production of z man years for its production, then the true energy requirement is given by

$$\mathrm{GER} = y + z \begin{bmatrix} \text{energy use per year for life} \\ \text{support of worker and family} \end{bmatrix} - \frac{zG}{n} \qquad (1)$$

It is common energy analytic procedure to assume that the second and third terms in (1) are equal, so that there is no need to compute either the national average energy consumption or the energy for life support for workers engaged in making the product of interest. Thus in (1) the

GER would normally be counted as 'y'.

If the quality (and hence pay) of the z workers is above the national average, then G/n will be less than the actual life support energy, and the quoted GER will be somewhat low, and vice versa. No detailed studies have yet been made to examine how much error is actually introduced by omitting this correcting factor, though there are several studies extant which demonstrate that energy use rises with income, though not in any linear manner.

2.1.3 Energy and Fuel

The word energy is used in the thermodynamic sense, and therefore has a number only when related to some standard state, taken as one bar pressure and 273.15 K. An energy resource can be given an energy value by considering the heat that would be developed if that resource was combusted under standard conditions. Most energy resources are not ready for use by the economic system, and are processed to produce fuels. In this paper a fuel is defined as a processed energy resource available for use by the demand sector of the economy. In Section 1 the distinction was made between heat (enthalpy) and work. Table 1 from the American Physical Society /49/ shows the difference between heat and available work for a number of common fuels.

Table 1 Enthalpy and Available Work of Combustion of Some Fuels

<u>Source</u>: Energy Conservation Study, American Physical Society, /49/

[Calculations are for combustion in air yielding a liquid H_2O product (gross enthalpy of combustion) at 1 bar pressure and 273.15K. Energies in the upper part of the table are in kJ per mole of fuel. Available work is given in other units in the lower part of the table.]

Energy Terms	Hydrogen H_2	Carbon C (to CO_2)	Carbon Monoxide CO	Methane CH_4	Ethane C_2H_6	Propane C_3H_8	Ethylene C_2H_4	Liquid Octane C_8H_{18}
Heat of combustion ($-\Delta H$)	285.2	393.6	282.7	890.1	1559.4	2219.4	1410.5	5467.2
Available work without diffusion (A)	233.8	394.4	256.8	813.2	1460.3	2099	1326.8	5274.8
Percentage change from $\lvert \Delta H \rvert$ to A	-18%	+0.2%	-9.2%	-8.6%	-6.4%	-5.4%	-5.9%	-3.5%
Available work								
MJ/kg	116	32.9	9.17	50.7	48.6	47.6	47.3	46.2

2.1.4 Work

Work is used throughout in the thermodynamic sense, not in the sense of time spent at a place of work. It would be measured in kg-metres, horse-power hours, or their energy equivalents.

3. Uses

3.1 Thermodynamic Limits to Technological Progress

Economic projections depend to a great extent upon assumptions of technological progress. Yet economic analysis per se offers no guide to what progress may be anticipated. As an example, take the case of ammonia production. This valuable nitrogen-containing chemical, which has changed the face of agriculture, was first synthesised by an electric arc process, using cheap hydro-electric power in Norway. It went through many transitions, as one technological improvement followed another. Today it is made by some variation of the Haber-Bosch process, in which natural gas and air (which contains nitrogen) catalytically react to form ammonia plus by-products. If one plots the logarithm of the cost of ammonia in constant money units against time, an almost straight line plot is obtained right up to the early 1970s (Figure 1). The temptation to extrapolate this straight line forward in time is clearly very great, Eventually it costs nothing! The plot in real money terms (Figure 2) gives very little information on future trends.

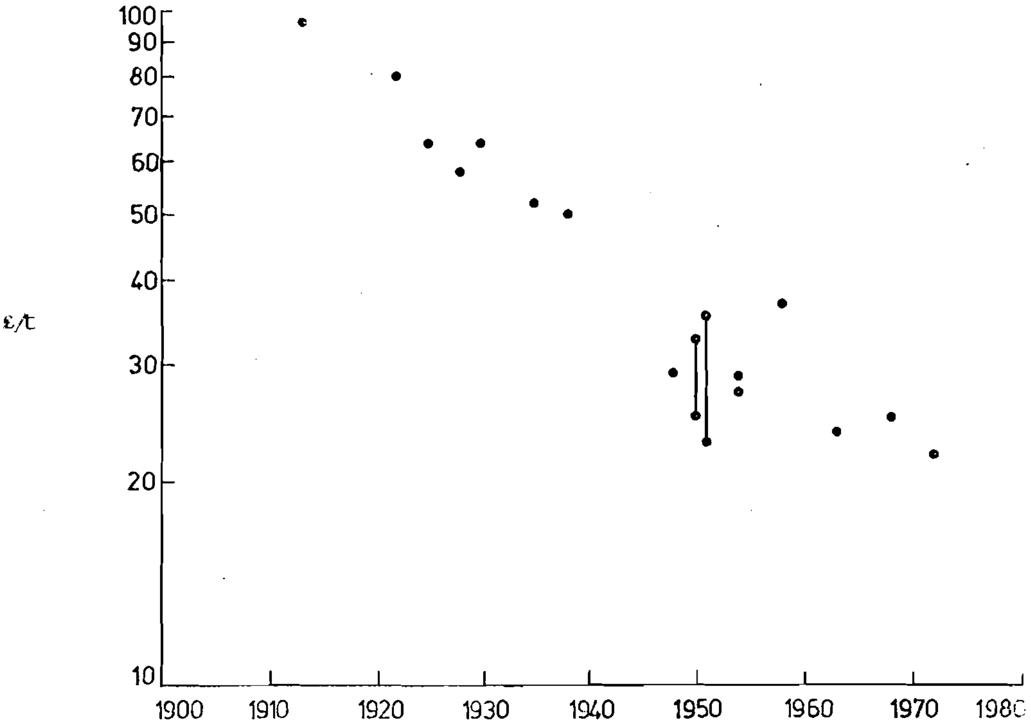

Figure 1 Price of ammonia in UK: relative prices (1970£)

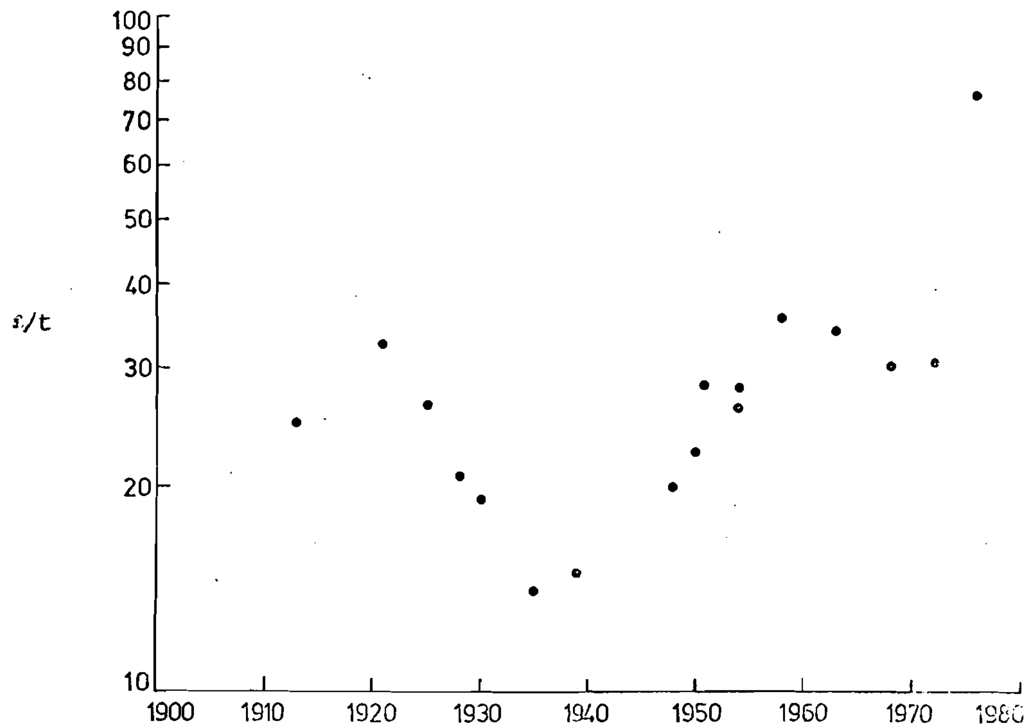

Figure 2 Price of ammonia in UK; real prices

Is there a temporary lull in technological progress or do we witness the end of an era?

If one makes an energy analysis of ammonia production, and plots the logarithm of GER (MJ/kg) against time, one does not obtain a straight line plot (Figure 3). Rather it asymptotes towards the thermodynamic limit, that is to say, the known theoretical enthalpy or free energy required for the formation of ammonia. It is quite impossible to devise a process that will produce ammonia for a smaller amount of energy, because the formation process is a non-spontaneous process, and so requires a decrease in entropy for its formation, at the expense of an increase in entropy outside the subsystem. This amount of energy is about 17.5 MJ/kg of ammonia produced. But such thermodynamic calculations apply only to reversible processes that proceed at an infinitesimally slow rate. In the real world, where products must be made at finite rates, irreversibilities such as heat transfer demand that somewhat more than the theoretical amount of energy be used. In a study carried out by J. Fleming /19/ it was found that technological progress ceased at an energy cost of about 2.5 times the theoretical minimum. Certainly if one does a chemical engineering analysis of a large ammonia plant it is quickly apparent that virtually all possibilities of improvement have been made, including those of economies of scale. The most efficient ammonia plants are now on the scale of 300.000 t.[1]

My judgement is that from now on in terms of gross energy resource, the marginal energy requirement of ammonia will rise, not fall, though, as old plants are replaced by new, the global average GER of ammonia may still continue to fall for some time yet.

[1] t means metric tons throughout this paper

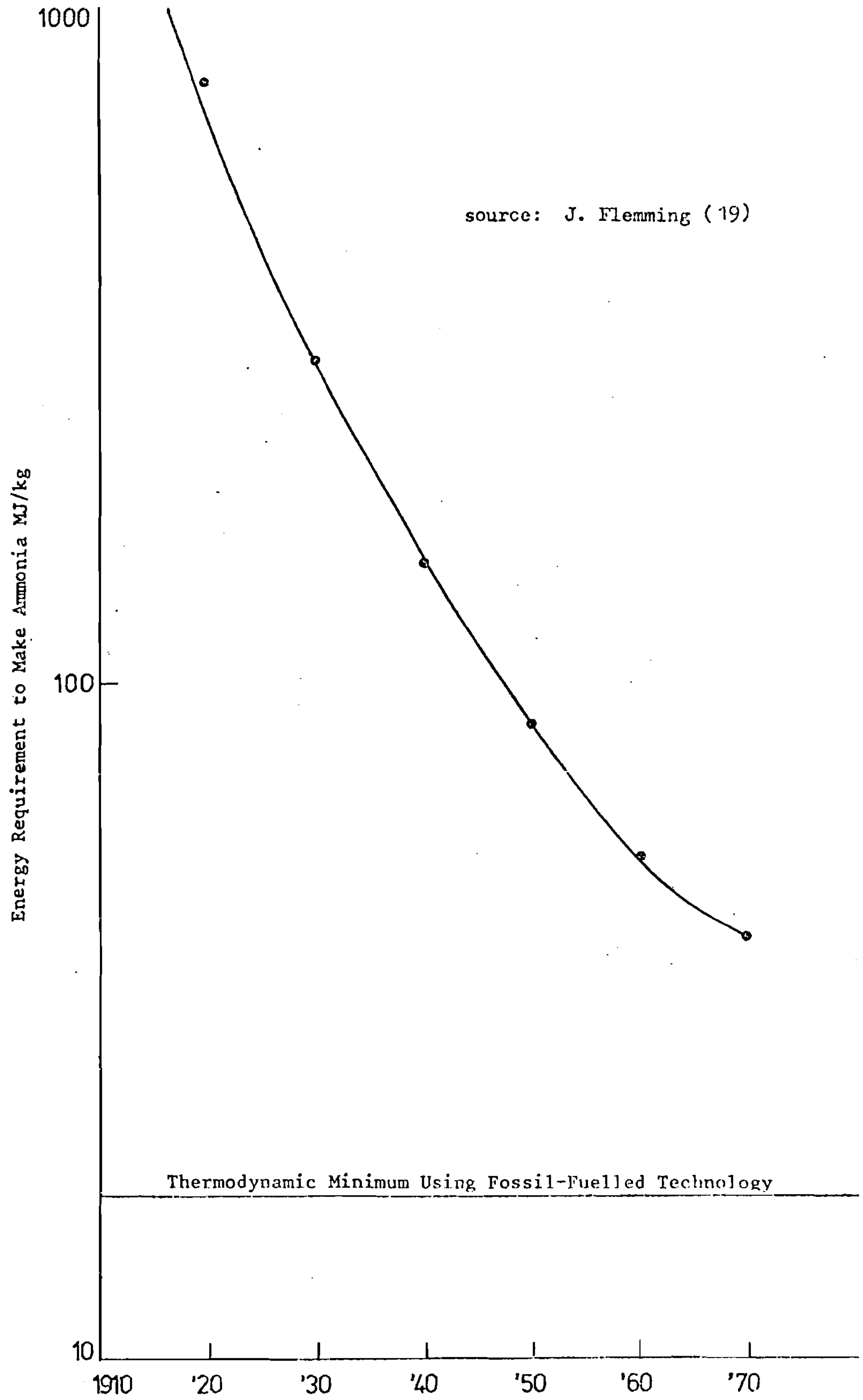

Figure 3 Gross Energy Requirement for Ammonia Production

3.2 Waste

If the essence of conservation is the avoidance of waste, thermodynamic calculations provide one means of determining the scope for reducing waste. Table 2 summarises some published figures /20/. The impression given is somewhat analogous to the ammonia example in Section 3.1, namely that further technological progress is undoubtedly possible. The IFIAS workshop adopted the convention of defining a waste factor as follows:

$$\text{waste factor} = \frac{\begin{array}{c}\text{actual free energy to}\\ \text{effect transformation}\end{array} - \begin{array}{c}\text{theoretical free}\\ \text{energy use}\end{array}}{\text{actual free energy use}}$$

Such a factor approaches zero in a perfect system. There are a number of objections to this definition. Firstly, it is conceptually more useful to have a definition that approaches unity at perfection, and is less than unity otherwise. But the principal objection, and this is being examined by the CCMS committee of NATO, is that there is a temptation to look at Table 2 and say to oneself that clearly the paper industry is less energetically efficient than the oil industry, which in turn is less efficient than the iron industry. This may not be the case, for unless one has made a technological study of the irreversibilities in the process in question, one cannot come to firm conclusions. Nevertheless the waste factor, however defined, if used in a time series analysis of one commodity can give one a good insight to technological progress and impending technological limits.

Table 2 Free energy use - actual and ideal; (sources: E.P. Gyftopolous et al. /20/, and S. Berry and M. Fels /13/.

Product	ΔG Actual for Industry in US in 1968 MJ/kg	ΔG_{ideal}	Waste Factor
Coking of coal	2.8	-.38	1.13
Iron	30.1	6.3	.76
Gasoline	4.4	.4	.9
Paper	40	.2	1.005
Aluminium	200	26.3	.87
Cement	8.2	.8	.9
Steel from Fe	21.3	2.0	1.19
Zinc smelting	58	-1.4	1.02

It is worth noting, in passing, that this sort of analysis is not new, but has been carried out by process engineers ever since thermodynamics was incorporated into their training. Most industrial organisations make their own energy balances, though few have made such a fetish of it as Dow Chemical, USA, which sets energy targets for its plant managers, apparently with great success /21/.

3.3 Conservation

It quickly becomes apparent in any practical conservation measure that conservation is necessarily preceded by investment. Of course, one may conserve energy by abstaining, either voluntarily or through taxes, but for the purpose of this paper such a conservation shall be treated as a form of rationing, since it calls for modification of personal behaviour outside the area of free choice.

One of the most familiar examples is the addition of insulation to a house to reduce its energy consumption for space heating. Here, apparently, the objective function is energy, not money. We would, as an aside, remark that this is an inconsistent attitude. If the objective function for, let us say, production, is money, then it should remain so for space heating. Yet many people who are otherwise economically minded, switch to an energy analysis mode of thought when confronted with a space heating conservation problem.

Let us first state the parameters of the problem and its solution. A poorly insulated house uses up more energy to heat a given space than a well insulated house. There are records of 90 m^2 Swedish houses that are capable of being maintained at 20^{o}C in mid-winter temperatures with an input of only 3 kW of heat /22/. A similarly sized English house built to the standards of the 1960s would require about 12 kW to attain the same comfort level in a less cold climate.

The English house may be improved by better insulation. Insulation means investment. Investment means added materials and labour. Materials require energy in their manufacture. Hence an energy analysis will examine the trade-off between added investment (in energy terms) and energy saved, while an economic analysis will examine the money or energy saved per unit of money invested.

Table 3 gives the outcome of such an analysis /23/ applied to a 90 m^2 public authority house built for rent in Scotland in 1976. The house, one of several hundred units in a new town, was built to 1976 standards of insulation, reflecting existing economic assessments of heating and construction costs.

Table 3 Lifetime cost of house

House type	(a) Public Investment Analysis			(b) National Investment Analysis			(c) Total Energy Analysis GJ
	0%	4%	7%	0%	4%	7%	
Mark I	9976	12022	15693	9579	11357	14543	15966
Mark II	9268	10504	12724	9049	10139	12093	10205
Mark III	10049	11167	13175	9937	10980	12851	10186

The table shows three modifications of the house. Mark I is the standard house with gas central heating. The house is costed for its construction, maintenance and operation over its anticipated lifetime of 60 years, all reduced to "net present value" (NPV) as is customary with economic evaluations. In Scotland, where the study was done, the method is known as Public Investment Analysis and utilises a standard discount rate of 10%

recommended by the Treasury Department of the UK Government. The energy requirement is assessed using known climatic data, and a fairly sophisticated method of assessing heat loss from the house. The GER of the fuels used in the house are those published by the Building Research Station of the UK, which differ slightly, but not seriously, from other, more rigorous calculations.

The GER of the house is possibly the most detailed ever made of a house, for it was obtained from a quantity Survey in which every last nail and screw is listed. The materials were grouped into 247 classes of material, for which GER figures were computed. The final result of some 700 GJ is considerably higher than figures often quoted for house construction, but previous studies have tended to consider only primary physical inputs and not the entire system. Typical of such an incomplete study is that of the E. Gardner and M. Smith /24/, recently published, in which data are given in GERs and some in process energy requirements, and no account is taken of many items of a manufactured nature, nor on-site energy use.

Mark II is a well insulated house with double glazing, polyurethane foam in the cavity wall, and better sealing in the door and windows to cut down adventitious air changes. Mark III replaces the gas central heating in the insulated house with an air heat exchange heat pump.

Public investment analysis (that is economic analysis using guidelines laid down by the UK Treasury) shows a small advantage for the better insulated house and a very slight advantage for the heat pump. This calculation raises the problem of what discount rates to use. When the calculation allowed for speculative rises in energy prices (see Table 3), the economic conclusions were firmly in favour of house insulation and heat pumps. But of course, how does one predict future energy prices?

Energy analysis suggests a huge advantage for better insulation, equal to a 270 return per annum on the added energy investment. It suggests a further advantage for replacing gas central heating with a heat pump, but the return on (energy) investment is less spectacular - 37% per annum.

How should one interpret such results? The outcome of the economic analysis is entirely predicated on two unknowns - the discount rate and the future price of energy. The energy analysis method contains no such uncertainties, but ignores time as an element in decision making. However, if the analyst decides to use the energy analysis approach, then what is his procedure? The insulation of one house requires a certain investment in energy spread over a short time, and is followed by a period of diminished energy use, so that energy investment is eventually paid back,usually referred to as the pay-back time. Ten thousand houses simply produce a result ten thousand times greater. The dynamics of changing a system of poorly-insulated houses to better ones requires the development of a dynamic model. Either one tests the output of such a model against a number of scenarios or, having determined an energetic solution determines the economic sanctions (perhaps tax rebates, subsidies, etc.) which could create the necessary incentives.

In the end, however, such analysis cannot be isolated from trends within the total system, which must include trends in energy production (e.g. more or less electricity), trends in utilisation systems (whether heat pumps will become cheaper, or more efficient), and trends in social behaviour (will people take gains in cost of space heating in more comfort or in more power to spend elsewhere). Chapman /50/ for example has shown that taking the system as a whole the electric route could be energetically superior to the petrol driven car in the UK.

3.4 Energy, the Determinant of Cost?

Any suggestion that energy may be the determinant of cost immediately brings the charge of trying to introduce an energy theory of value. As will be explained in Section 4.2, such a theory would be as fallacious as a labour theory of value, or any other single-parameter theory. Nevertheless there is some evidence to suggest that energy analysis can allow one to predict relative costs of prime materials. Without at this point putting forward any explanation for the results, let us look at the work of W.G. Phillips and D.P. Edwards /25/ and their associates. They found that they were able to predict the price of metals on the London metal exchange simply by computing the Gibbs free energy - which is close to available work (see Table 1) - of the formation of the metal from its ores at current average ore grade.

Figure 4 reproduces their plot. The correlation is quite remarkable, and fits in well with the ideas put forwad in section 4.2.

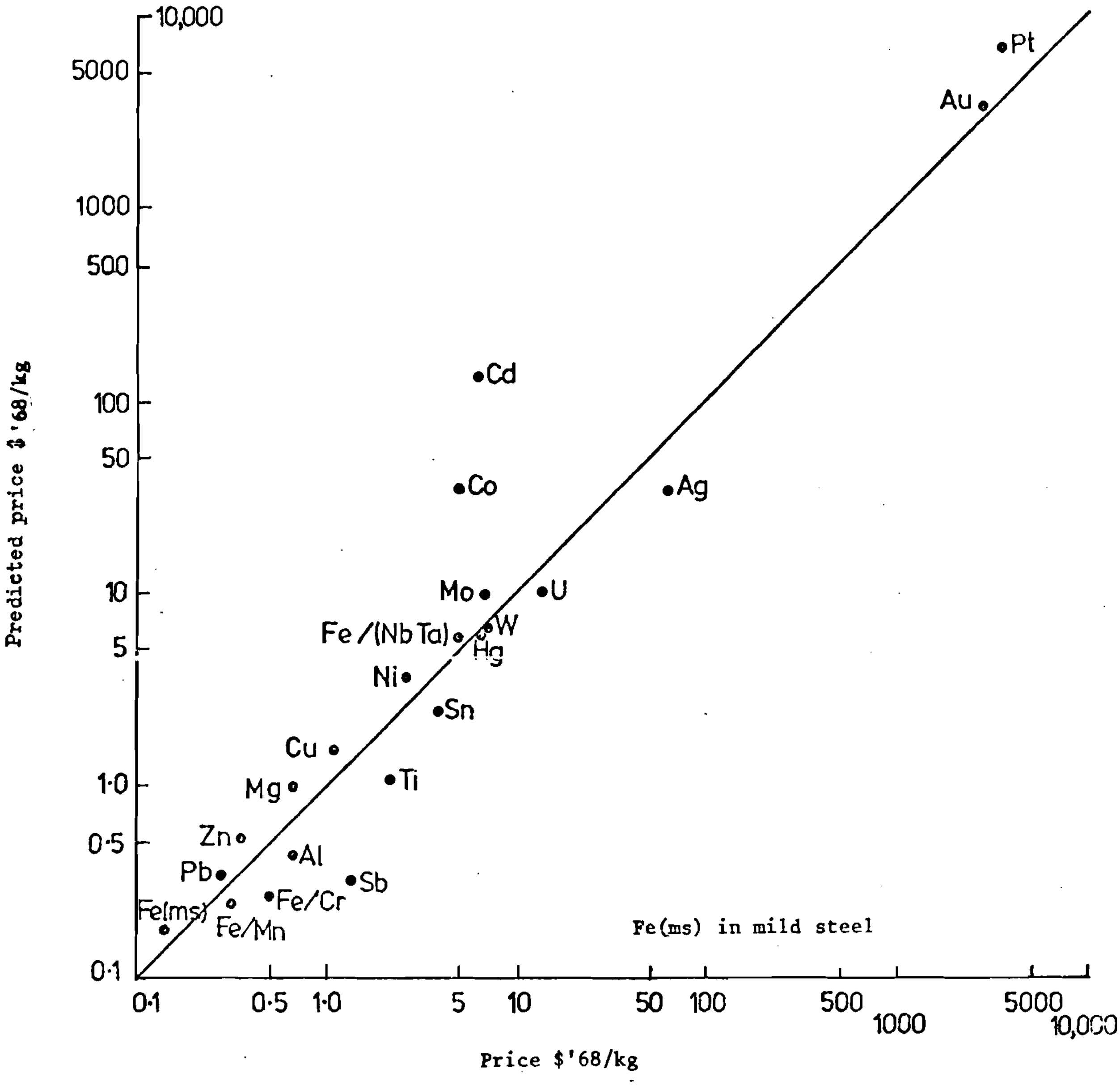

Figure 4 Metal prices andore grades predicted versus actual price; source: W.G.Phillips and D.P.Edwards /25/.

3.5 Energy Requirement for Energy

A primitive peasant, assessing his days of work upon the land, may ask himself how many days he must work per year in order to feed himself and his family. If he finds he must work every daylight hour of every day, then he has no capacity to widen his system, for his entire life is taken up with meeting his own basic needs. A peasant whose annual labour in the fields feeds three other people to work on other activities is living a community capable of expansion in many directions of development. It is a useful parameter to know the fraction of man's time that must be taken up in supplying him with food, and economists looking at primitive communities do just that.

In the same sense it is surely valuable to ask how much of the energy being produced by an energy system is needed to drive that system. If all the energy produced is used up in driving the system, none is left for other purposes, and the system is pointless. (We do not say this of the man who gives all his time to producing his food, because we yield to man the right to live.) The IFIAS workshop /1/ gave this matter some attention, and proposed a parameter called the "energy requirement for energy" (ERE). Figure 5 depicts the extraction and subsequent processing of a resource in the ground to a fuel (see Section 2.1.3, Terminology).

The 'energy transformation system' box (ETS) contains all the processes that occur in order to produce a unit of fuel y. 'y' may be in kilograms or barrels or in MJ. If the last, it is the heat that would be released if 'y' was burnt under standard conditions (see Section 2.1.3).

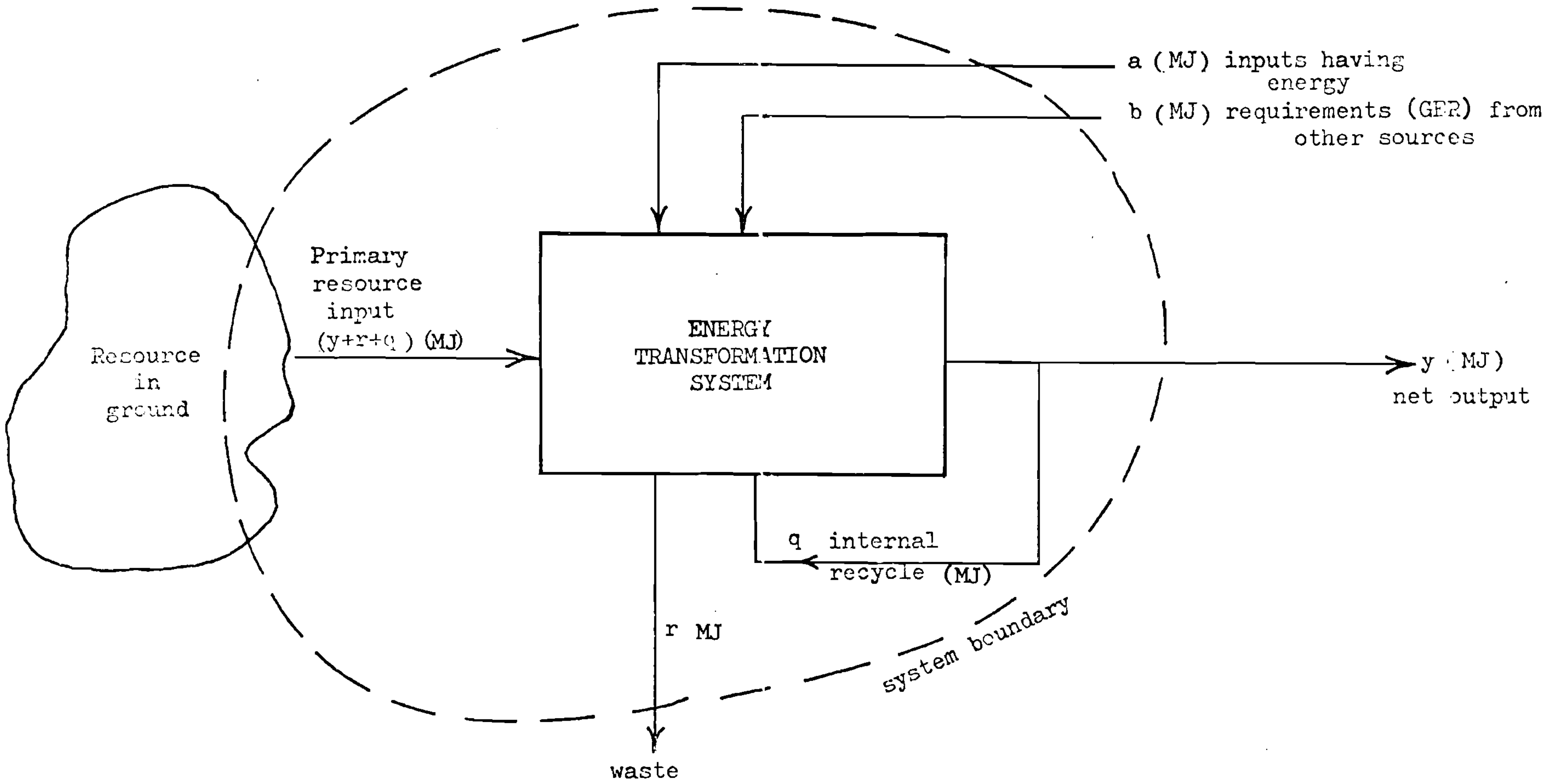

Figure 5 A systems view of the energy transformation system.

For convenience let us visualise the ETS as a crude oil refinery producing a unique product, y. The ETS will include all prior activities like exploration, production, transportation by pipe-line or tanker. Some of the product y (or others), q, is recycled back into the ETS. It may be fuel for tankers, oil to heat furnaces, and so on. There may be some waste, r. For example, in a shale refinery the waste rock still contains some hydrocarbons. The amount of resource needed, therefore, to yield a unit 'y' is y + r + q. However, it is more than likely that in setting up the ETS external inputs were required, and during operation may continue to be required. For example, steel and cement may have been required to build the ETS, and externally produced electricity and materials may be required to operate it. Let us list two such inputs and compute them as so much per unit of 'y', say a + b. Since a + b must themselves have been the result of some energy resource being extracted elsewhere, they are couched in GER terms.

Thus the total amount of resource required to deliver a unit of 'y' is

$$\text{GER fuel} = (y + r + q + a + b) \qquad \text{equation 2}$$

Under the IFIAS conventions, this is the GER of the resource type y, per unit of product. The ERE is therefore

$$(y + r + q + a + b)/y \qquad \text{equation 3}$$

expressed as MJ resource per MJ fuel, and is $\gg 1$.

3.5.1 Net Energy

The concept of the energy requirement for energy brings into need the concept of net energy. Concern for net energy has spread fast. At one time folk-lore had it that nuclear reactors were not net energy producers. A misquote in Newsweek in 1975 (though corrected the following week), spread the idea that shale oil was not a net energy producer. Net energy became a key pawn in the environmental lobby. In 1975 Congress was persuaded to pass a law (Public Law 93-577) making it mandatory for funding bodies to carry out a net energy analysis when evaluating R & D support. It was later appreciated that no-one had actually precisely defined net energy, and funded by the NSF, a net energy workshop was convened in Stanford, California, in August 1975 /12/. Most curiously the workshop ended by declining to formulate any algorithm for net energy.

We cannot, therefore draw upon a widely held consensus in proposing a parameter of net energy, and the following must be ascribed strictly to the author of this paper.

The reader is advised to look closely at the provenance of "net energy ratios", which abound in the literature but are not often comparable.

3.5.1.1 SESU Definition of Net Energy

Using Figure 5, the Strathclyde Energy Studies Unit (SESU) definition, net energy is defined net energy = y - (a + b + ... all external inputs expressed as GER/y

equation 4

This definition omits 'r + q' from the computation. In this way, when (a + b + ...) = y, extraction of the resource ceases to be meaningful. There is as much energy around if one does nothing. A point of futility has been reached, for by not extracting the resource there is available to the economy as much energy as there is by extracting it. The only exception can be when y has a quality (however expressed) greater than inputs 'a + b', as in the case of the product 'y' being electricity[2]. On the other hand (r+ q) can be (infinitely) large without reaching a point of futility. In the case of extraction of tar sands, (r + q) are sizeable.

Clearly, depending on the values of r and q, the GER of a fuel could vary widely even at the point of futility. When a and b are zero, then the GER must approach infinity before being a net energy loser. If the total system were the total work system, then this would be the way to sum it. Table 4 lists GER and net energy figures derived from the energy analysis work of the Colorado State Energy Research Institute /26/.

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[2]An interesting variation of the problem is when 'y' is a food. Some analysts (e.g. Leach /28/) like to express a food product in units of metabolizable calories, and so sompute an "energy ratio", which often exceeds unity, that is, produces negative net energy. Usually energy ratio is expressed as the inverse of ERE.

The IFIAS GER definition successfully removes any value judgement. Thus one might find that it took 13 MJ of energy resource to deliver 1 kWh of electricity, and 3.9 MJ to deliver 1 kWh (thermal) of coal. Like money, one does not expect a single number to tell one everything one needs to know. One must also know that the work potential of 1 kWh of electricity far exceeds that of 1 kWh (thermal) of coal.

Table 4 GER and net energy (SESU) for US fuels /26/.

	GER	SESU Net Energy
Natural Gas	1.2	.96
High calorific value gas from surface and underground coal	1.67	.96
Gasoline from petroleum	1.2	.89
Gasoline from underground shale	1.76	.84
Gasoline from surface shale	1.75	.83
Gasoline from coal	1.65	.84
Coal	1.03	.97
Electricity from		
Natural gas	3.82	.88
Coal	3.48	.89
Oil	3.59	.89
Oil shale	5.21	.74

3.5.2 Net Energy of Bio-Mass Systems

Of recent years bio-mass systems have been put forward as solutions to the energy problem. C.Lewis /29,47/ has made a study of such systems and has come up with some pessimistic results. Unlike the use of fossil or fissile fuels, bio-mass systems require much land. Lewis' method of analysis can

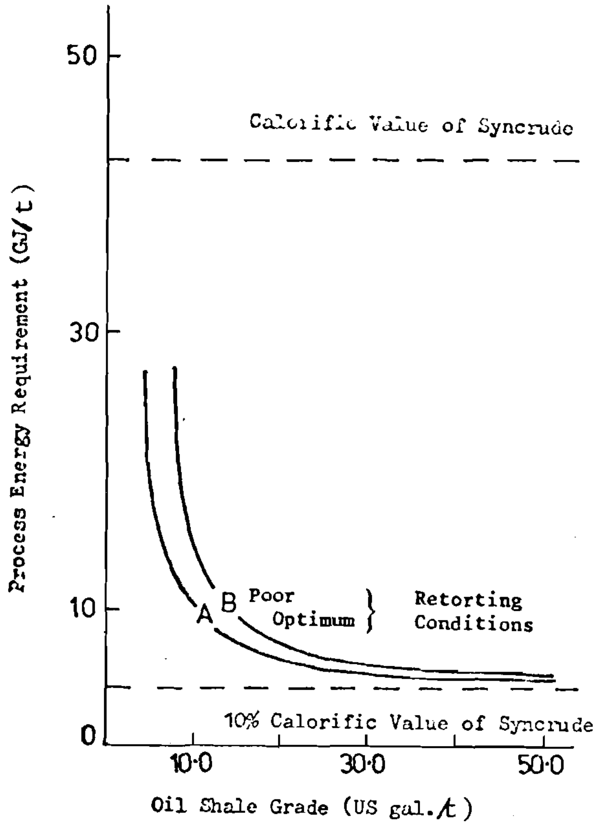

Figure 6 Process energy requirement for the production of Syncrude from various grades of oil shale, source P.Chapmand and D.Hemming/27/

be summarised in Figure 7 in which the box represents the land area required to produce a system output of y MJ of fuel. He examined a number of systems which were thought to be economically viable, and his results are summarised in Table 5. The key column is net energy, expressed as GJ/ha-yr. Note that solar energy is treated as a free input because it is a flux source available whether utilised or not. Very few intensive biomass systems, it seems, are net energy producers[3]. Those that are, apart from straw, are untested, the calculations having been done upon paper studies by other workers. The energy crop concept (agriculture for biomass) of the Stanford Research Institute is somewhat predicated upon the energy requirement for water supply, and though the idea looks attractive,

[3] C. Lewis examined mainly intensive systems. Many non-intensive ones are net energy producers, but output per hectare is very low indeed.

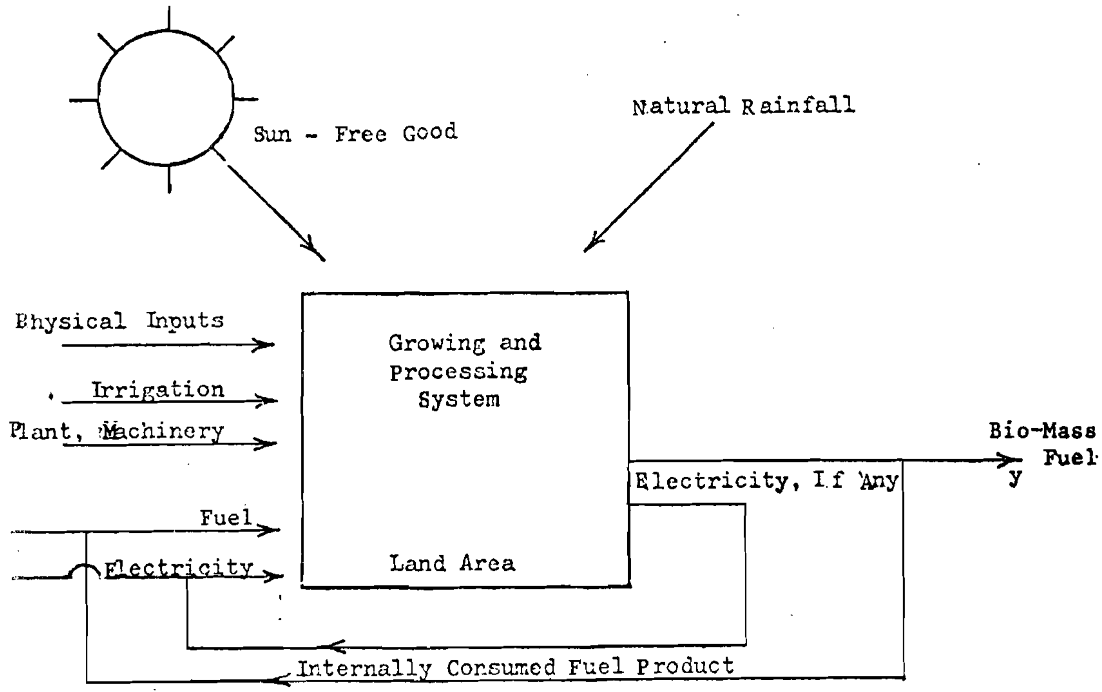

Figure 7 Energy systems analysis of bio-mass production

the location studied, New Mexico, would call for piping vast quantities of water over more than 800 miles from the Mississippi river. The output of 1000 GJ/ha-yr is very impressive, but would nevertheless entail, in the US context, the dedication of some $70 \cdot 10^6$ hectares of land to furnish current US needs. Nevertheless bio-energy systems do offer a valuable potential to less developed rural communities, and there are promising new bio-technologies.

3.5.3 Net Energy Analysis and Economic Analysis

In equation 2 inputs a + b + ... emanate from other parts of the economic system and therefore have a determinable price. Elements r and q

Table 5 Data on bio-mass production and its conversion to fuel, source: C.Lewis /29,47/

System and Product	Productivity (t/ha yr)	Net Energy (GJ/ha yr)	Net Energy (GJ/t)	GER Product (GJ/t)	Man-Hour /t	Key Inputs
Wheat cultivation --straw	2.6	+ 39	+ 15	0.6	2	fertilizer, fossil fuel
Straw --ethanol	0.7[a]	- 138	-195	222	20	N,P, fossil fuel
Biomass (energy crops) growth	68	+1090	+ 16	1.25	0.3	water[b], fertilizer
Timber --ethanol (via enzymatic hydrolysis)	0.35	- 74	-212	239[c]	21[c]	N,P, fossil fuel
Timber --ethanol (via acid hydrolysis)	0.22	- 16	- 71	98[c]	120[c]	N,P,H_2SO_4, fossil fuel
Casava growth (for starch)--ethanol	2.1	- 69	- 33	60	25	N,P, fossil fuel
Sugarcane growth and sugar --ethanol[d]	17	+ 51	+ 3	24	6.8	N,P, fossil fuel
Sugarcane growth and (sugar + bagasse)--ethanol	25	-1750	- 70	97	17	N,P, fossil fuel
Algae growth on sewage[e]	25	- 850	- 34	57	34	fossil fuel (at present)
Probable future growth of algae on sewage	25	+ 125	+ 5	18	34	fossil fuel flocculating agents
Tentative future algal growth --methane	5.6	- 627	-112	168	200	fossil fuel
Livestock waste --methane[f]	0.01	- 0.88	- 88	144	237	fossil fuel (at present)

[a] The productivity figure for ethanol is based on 2.6 t straw/ha yr;

[b] Water is assumed to be sufficient, but see Section 2 for a discussion of the implications of water deficiency;

[c] The greater GER ethanol from timber via the enzymatic hydrolysis route over that via the acid hydrolysis path is somewhat compensated by the 470% increase in labour requirements of the latter rather outmoded system;

[d] The sugarcane growth and sugar-ethanol route system is the most favourable as a marginal net energy producer using current technology;

[e] As sewage-grown algae are themselves a net energy loss using current methods, the conversion of their energy content into methane will greatly magnify this loss;

[f] Although an overall net energy loss, the production of methane from farm waste is generally considered to be a mere by-product of an effluent treatment system. A similar attitude may be adopted when considering methane evolution from algae grown on domestic organic sewage.

have no value if the resource is unexploited. In an economic costing of a tentative process, r and q have an impact only in so far as they affect the plant size, that is, capital needs or environmental impacts. Direct costs tend to be more closely related to the ratio (a + b + ...)/y, and not to the total amount of prime resource use. In this sense it is closely akin to net energy analysis, and so one might expect to find net energy analysis providing some insights into relative costs, as Edwards and Phillips did for metals /25/.

The well known case is that of US oil from shale. Economic predictions made in 1972 showed that shale oil would be economically viable when ground oil reached a price of \$ 11 per barrel, while post 1973 calculations of oil from shale showed a viability at \$ 18, and recently these figures have been raised further. Always the new figure is somewhat greater than current ground oil prices. Can one make any deduction from the figures shown in Table 6 below?

Table 6 Relative energy requirements of US ground oil and shale oil

	GER	Net Energy$_{SESU}$
Gasoline from ground oil, western USA	1.2	.89
Gasoline from Colorado shale	1.75	.83
Ratio of shale oil/ground oil	1.35	1.07

The deduction surely is that in shale oil the terms (a + b ...)/y are larger than for ground oil, and that therefore a given ouput of oil from shale calls for more input from the economic system than does ground oil. Hence, no matter the price of ground oil, shale remains uneconomic unless given tax or depreciation advantages.

Uranium is an example of divergent thought on this matter. Several energy analyses now exist on nuclear power systems; with respect to uranium they adopt one of three conventions:

(1) Treat uranium as a non-energy input, i.e. $y + r + q = 0$ in equation 1. This is done by P. Rotty et al. at Oak Ridge /30/

(2) Give uranium an energy value equal to useful heat captured in the reactor. 'y' per unit resource use is then a function of the system, and of current technology. This system is adopted in UK and EEC energy statistics.

(3) Treat uranium as a fuel having an energy content equal to its fission energy, whether used or not. This method is analogous to that internationally adopted for fossil fuels for over a hundred years.

Each of these methods produces different GER values (method 3 gives about 20 MJ/kWh for a PWR), but the same SESU net energy.

3.6 Dynamic Net Energy Analysis

Section 3.5 must arouse some anxiety in the mind of the analyst. One besetting problem is where to draw the system boundary, and though in Figure 5 the individual energy transformation system (ETS) has a system boundary drawn around it, so that upstream it is the resource in the ground and downstream it is the fuel delivered to the demand sector, there are nevertheless continuing doubts about the correct interpretation of the external inputs, not least of which is the evaluation to be put upon electricity. Often some assumption is made of 33% efficiency, yielding 1 kWh electricity equals 10.8 MJ. A better approach is to make a total energy systems analysis to determine total system net energy. This has been done by A.R. Gloyne and R. Peckham /31/ for the entire EEC energy system. Their model is a simulation model. There is no need to introduce parameters of gross energy requirement as in equation 2 or net energy as in equation 4. Their model produces two outputs from the sum of all the energy transformation systems in the EEC domain: thermal energy and electrical energy. These two outputs enter the demand sector. The ETS's draw back from the demand sector inputs for maintenance, construction, operation and so on, couched in thermal and electrical units. Depreciation and new construction are dealt with as they occur. Resources are depleted according to scenarios laid down through economic or political analysis. Such a model generates an instantaneous value for the resource requirement of electricity, and the total system net energy. It answers accurately the question; what is the total resource requirement to satisfy a given energy demand? Energy mix can be changed according to a pre-conceived policy, whether computed by economic methods or dictated by strategic or political methods, or it can be changed according to marginal net energy values of different fuel mixes. The data entering such a model corresponds exactly to that formulated in the IIASA Energy Group's WELMM study by M. Grenon and associates /36/.

Given access to WELMM type data, the output of such a model can be prolific, yielding all relevant factors of energy production.

3.7 Energy Requirement of Energy: North Sea Oil

Modelling studies such as described in Section 3.6 require information on the changing inputs per unit of output as the quality of a resource changes. Energy analysis provides one with the tool to make that study, but at considerable cost of time and effort. For example, it took three man months to establish the energy required for construction, operation, exploration, production etc, for one field of the North Sea. E. Mcleod's numbers for the Forties field /32/ are listed in Table 7 below. In principle, if one was to make a similar study for all possible North Sea oil fields, one could emerge with a value for ERE (energy requirement for energy) as a function of amount of oil extracted, and when secondary or tertiary methods of recovery occur, take them into account as an internal recycle. D. Hemming /27/ has attempted to do this for the North Sea, though his data base is still very thin. The general thrust of his work is depicted in Figure 8.

Table 7 Energy Requirements of the Forties Oil Field, source: E.McLeod /32/

	Capital	Direct	Total
	10^6 GJ		
Exploration/evaluation	.42	1.31	1.73
Construction/installation of production platforms	2.92	2.78	5.70
Under-sea pipeline	6.12	3.77	9.89
Production drilling	3.64	2.59	6.23
On-shore installations	6.1	.33	6.43
Production	23.0	107.6	130.6
Total	42.2	118.4	160.5

Average over life time of field 0.645 GJ equivalent to yield SESU Net Energy (average) of 0.985. This value is to bring crude oil to the refinery gate, not to produce refined oil.

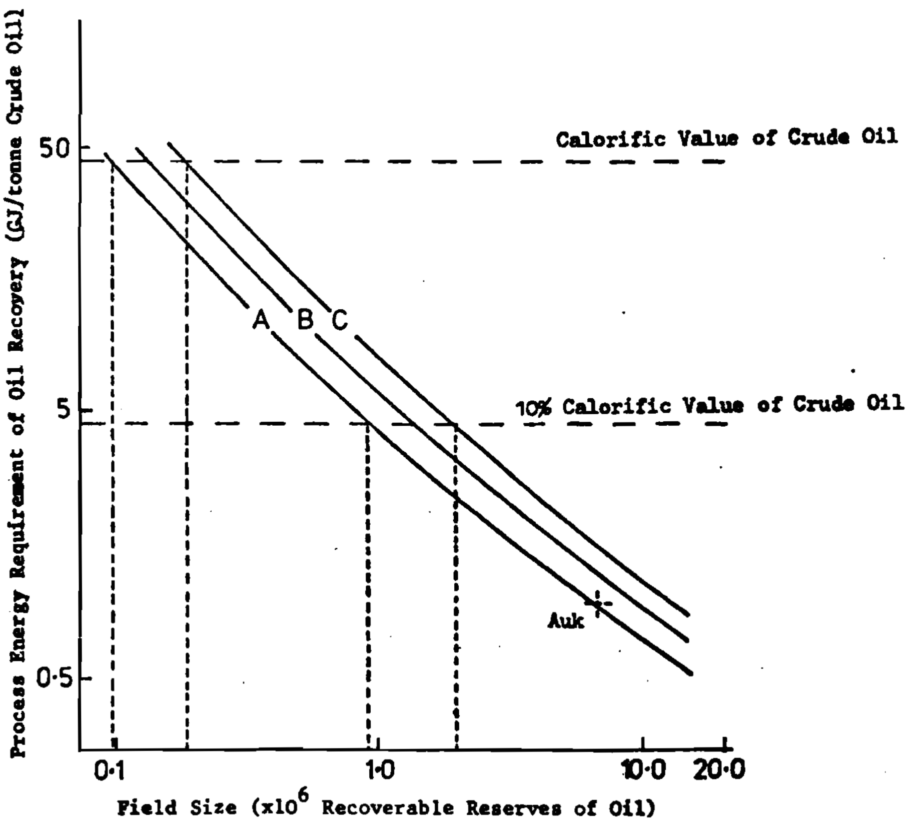

Figure 8 North Sea oil fields: variation of energy requirements of oil recovery with field size; water depth (m)/average success rate A (87/1:8), B(120/1:8), C (120/1:16); source P.Chapman and D. Hemming /27/.

4. New Concepts

The question is frequently posed "what is the utility of energy analysis?", and is followed with the enquiry "what can energy analysis do that money cannot do better?". Let us concede at once that for making a decision today money is an extremely sensitive way of summing all factors into one numeraire. Today's price compared with today's money supply enters into every person's brain like two inputs to a sophisticated computer programme, and allows each to make his or her choice. This sophistication should not blind us to the fact that money is a symbol. It is a value judgement. We see this at its clearest on those occasions when confidence ebbs in the money system, as it did in the Germany of 1920. We see it when depositors lose confidence in a bank, as happened with the Intra Bank in the Lebanon some years ago.

An important factor concerning money is that its supply is not based upon a stock of physical or human resources but on our skill in maintaining its circulation. Through the banking system a given quantity of money can be lent several times over before the original debt is settled, thus increasing the money supply without increasing the resource base. Both the willingness to lend money and the willingness to borrow reflect conditions of confidence. Those who choose to live off money, that is to say by the craft of lending at interest, are obliged to find borrowers at all times, even if, as at present in the UK and Italy, money is effectively lent at a negative interest rate. This is bearable, because the borrowed money often finds its way back to the lender, who rents it out again.

Under such circumstances equilibrium based upon the intersection of supply demand curves is a transient dependent on management of the money supply. It is too easy for bankers and governments to distort the intersection by altering the money supply.

These thoughts suggest that money, whatever its precision as a reckoner in the world of this instant, becomes an increasingly less adequate measure of future activities. Moreover, the economic horizon is limited entirely by the perceived discount rate. If this rate is 10%, then any event twenty-five years or more ahead has zero effect on economic decision making. The British Government faced with this fact in making its forestry policy (trees take more than 25 years to grow to maturity) was obliged to introduce a modified discount rate. The moment one modifies it by fiat, the logical basis of the original discount rate is brought into question.

Most energy modelling is presently done in money units, and such modelling raises two serious doubts (even when recourse is made to relative prices). The first is the uncertainty about future prices and the second the uncertainty about elasticities of supply and demand. The projection of past values entails as many assumptions as there are possibilities, while the concept of elasticity, though a very useful method of predicting what might happen tomorrow (since people's tastes don't change that quickly) can on occasion be hopelessly wrong. No econometric model predicted the sudden emergence of an OPEC cartel strong enough to create a step change in oil prices. It is entirely suspect for any period for ahead in time.

We can, at best, regard econometric modelling using the money numeraire and elasticities as a guide to the future trends in terms of current behaviour, knowledge, goals, prejudices and beliefs, and so regard them with increasing caution, as they move to the middle and distant future.

On the other hand, there is a need to have some handle on the future. Energy analysis offers some assistance. On the basis of Edwards and Phillips /25/ and the net energy discussion in Section 3.5 it would seem that net energy analysis may give a guide to future (relative) prices of energy.

4.1 World's Primary Resources

Table 8 depicts the world's primary resources. They fall into three categories: finite and non-consumable, renewable, and non-renewable.

Table 8 World's primary resources

	FORM	RESOURCE	SOME VARIABLES	
FINITE RESOURCES UNCONSUMABLE	STOCKS	LAND	QUALITY	LATITUDE
		ORE-BODIES	QUALITY	DISTRIBUTION
		WATER	ALTITUDE	DISTRIBUTION
		SEA	TEMPERATURE	LATITUDE
		AIR	CLIMATE	
	FLUXES	SOLAR ENERGY	SEASON	LATITUDE
		RAINFALL	UNCERTAINTY	DISTRIBUTION
RENEWABLE RESOURCES		PEOPLE	IDEAS QUALITY	TECHNOLOGY TRAINING
		ANIMALS	GENETIC	
		BIO MASS	LAND	INPUTS
NON RENEWABLE	ENERGY [NEGENTROPY]	FOSSIL	QUALITY DIVERSITY	DISTRIBUTION
		FISSILE	QUALITY	DISTRIBUTION
		FUSION	DILUTION	

4.1.1. Finite Non-Consumable Resources

On the finite resources there are those that are non-consumable, and those that are fluxes, to be instantly used or not at all.

Finite resources represent stocks, an inheritance of ore-bodies, sea-water, fresh water lakes, and air. When a metal is sequestered from an ore it is not consumed. Its entropy is reduced (it is made into more ordered atoms or structures). It may form some element of capital stock or some 'consumer' good but it is never consumed. The atom of iron in iron ore remains an atom of iron, whether turned into a car, or subsequently thrown on the scrap heap and returned to rust. There is, in addition, so much of every element on the earth that, as A. Weinberg /33/ has shown, we simply cannot run out.

What we run short of is high grade ores. Once gone we can in the last resort go to common clay or even sea water for all our needs. K. Dunham /34/, M. Slesser /35/, and A. Weinberg /33/ agree that the only physical limitation on the extraction of ores is the energy needed to get at them, and the resulting pollution from large amounts of waste.

Fluxes, on the other hand, represent resources which are only valuable if captured. The most important of these is solar radiation, about which we have a great deal of information. Its flux varies with season and latitude. Natural eco-systems have learnt to capture a small proportion of the incident energy, and theoretical bio-chemistry has elucidated reasons why even using optimum photo-synthetic pathways, no more than 4% to 5% of this incident energy can be captured. We are, however, at the beginning of contriving physical devices such as photo-voltaic devices which can better that figure.

4.1.2 Renewable Resources

Living things are renewable. In a totally unintensified world the balance of nature was established by a hierarchy of consumers which man, the hunter, managed to dominate. Today we utilise energy to stimulate output and to intensify, and in so doing we can multiply many-fold our stock of renewable resources-man, animals and plants. In a highly developed society we no longer regard a man or woman as source of work (see Section 2.1.4), but mostly as a decision maker, whether those decisions be that of company policy or controlling the machine that fills the milk cartons. Man as a renewable resource has the enormous advantage over other species that his evolution can be very fast. Through education and training, in one generation he can move from a primitive environment to a highly sophisticated one. He can increase and multiply, or choose to decline in numbers. He has a social conscience that makes him or her consider the next generation and its welfare.

4.1.3 Non-Renewable Resources

There is only one set of non-renewable resources[4], and that is our inherited stock of fossil, fissile or fusionable energy. Admittedly the stock is very large, but already we seem to be running up against some problem of maintaining the flow of useful fuels into our economic system.

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[4] Strictly speaking the sun, as a fusion reaction, is also non-renewable, so this statement depends on our time horizon.

We see at once that there is a distinction of quality between stocks and flows. We may judge the sophistication of a particular society by the number of electric motors per capita. These are valueless to us unless there is available to them a flow of electricity. The energy problem is therefore a fuel flow problem. It has a dual nature, because we also have a daily flow of dilute (if high grade) energy: the sun. However, we have not yet found a way to make use of that on a really large scale, and any discussion of the energy scene must for the moment centre around the manner in which energy stocks are turned into flows, and what energy does when it reaches the economic system. A moment's digression may help those with little acquaintance with thermodynamics.

The chemical equation for the burning of natural gas with air reads:

$$CH_4 + 2O_2 + N_2 \rightleftharpoons CO_2 + 2H_2O + N_2 \quad \Delta H = 55.7 \text{ MJ/kg methane.}$$

ΔH represents the heat given out by the combustion process. It is a spontaneous process. It cannot however occur spontaneously in the reverse direction. That is to say if we take some carbon dioxide and water (of which there is abundance in the air), no matter how long we wait, methane will never be formed[5]. To form methane requires an additional amount of energy, and the concept of entropy is introduced to effect the relation between the actual energy of combustion, ΔH, and the energy available to do useful things, the so-called free energy, ΔG. Free is not here in-

[5]This is not strictly true. A mixture of pure CO_2 and water vapour in the ratio of 1:2 (which does not occur in nature) has the potential to change to some methane and oxygen, but as the equilibrium constant is approximately 10^{-16}, the methane product is almost undetectably small, and may be ignored for practical purposes.

tended in an economic sense, but rather in the sense of that proportion of the energy which is actually free to do work, the rest being unavailable.

Our economic system is entirely taken up with carrying out non-spontaneous processes. The simplest way to perceive this is to consider a diffuse resource in the ground, being concentrated into a set of ordered molecules called a billet of iron, which is further ordered into sheet steel, and when blended with other similar processes, finally creates an automobile. We have created a very ordered thing indeed, and the non-renewable resource price we have paid is the destruction of order elsewhere. As was pointed out in Sections 3.1 and 3.2 in spite of our cleverness, we still use several times more energy to make something than the theoretical. That is a way of stating that everything we make increases the entropy of our world. R. Clausius, the German physicist who introduced the concept of entropy, remarked gloomily "Die Entropie der Welt strebt einem Maximum zu". Thus as we increase the production of goods, increasing with economic growth, we increase the number of ordered units in our environment and so decrease their entropy. We are at the same time, by a large factor, increasing the total system entropy, or as described in Section 1, consuming negentropy. It is a one-way process. The economist, N. Georgescu-Roegen /36/, has argued that eventually our entire energy supply will be taken up with maintaining existing systems, leaving nothing for development or expansion. No-one, however, has yet established if such a point is imminent or far off.

Broadly speaking, therefore, we can regard the consumption of fuels as the consumption of negentropy. However, we also enjoy a daily supply from the sun, whose negentropy we have scarcely learnt to use. Until we do so our existing economic system can only be sustained by the consumption of fuel stocks.

For those who still doubt this approach, a re-examination of Figure 4 is urged. The conversion of an ore into a metal is an exercise in reducing the entropy of the metal, and is measured not as heat, but as a reduction in entropy, through the Gibbs free energy criterion.

In everyday speech the word energy will continue to be used, but it is important to appreciate the word is really a surrogate for negentropy.

4.2 Energy - Labour Interpretation of Money

An economic production function may be written as follows, expanded to differentiate energy from other physical inputs:

$$Q \text{ (rate of production)} = \emptyset' (K,L,E,M) \qquad (5)$$

where

K is capital, in economic terms expressed as money;

L is labour, expressed as money cost;

E is energy;

M is materials.

One may visualise a trade-off between these inputs, for example between energy and labour, and, for a given simple system, argue that production will develop as the inputs grow and may be duly optimised.

Take now an energy analytical view of these four inputs. An energy analysis upon the materials will reveal a network of inputs going back to the ore in the ground, the energy in the ground, capital and labour.

An energy analysis of capital goods will likewise end up, when networked back, as materials, labour and energy. If the entire production system is networked back we are left with the relationship

$$Q = \phi\ (L, L', E, E') \qquad (6)$$

where

- L is current labour use-decision making;
- L' is past labour use-technology or know-how;
- E is current energy use;
- E' is past energy use-capital, duly depreciated.

In this model we see that no single parameter theory of value will suffice. We can see why W.G. Phillips' and D.P. Edward's /25/ plot (Figure 3.4) occurs. For all mining operations, the capital and labour inputs are presumably of much the same order, the key current variable being free energy.

I am much indebted to P. Chapman for a further development along these lines relating to the relation between capital and energy prices. Let us express the cost of a capital item, K, as

$$K = (X_L\ P_L + X_F\ P_F)\ (1 + \alpha\ I) \qquad (7)$$

where

X_L = total man-hours labour;

X_F = total quantity of fuel used;

P_L = price of labour/man-hour;

P_F = price of fuel/MJ;

I = interest rate;

α = profit, rent, etc.

Now for Power Stations in the UK $(1 + \alpha I)$ is about 1.5.

Simplifying,

$$K = (X_L + \frac{P_L}{P_F} + X_F)\ (1.5)$$

$$= 1.5\ P_F\ (X_L \beta + X_F) \qquad (8)$$

where

$\beta = P_L/P_F$.

An examination of long term trends in the UK by R. Echiburru /51/ showed that P_L/P_F has steadily increased. X_L, on the other hand tends to fall with improving productivity. As a first approximation, then, βX_L will tend to a stable value.

Thus, given a price rise, X_F may tend to fall under market forces, limited only by thermodynamic considerations. Hence $K \triangleq (\text{constant})(1 + X_F)P_F$. That is, the cost of capital in a direct function of energy price and content. Information theory may be the key to linking labour (as a decision making unit) and energy (as negentropy) into one parameter.

4.3 Energy Analysis and the WELMM Approach

In the WELMM approach /36/, the water, energy, land, man-power and material needs to satisfy a given energy strategy are to be evaluated. The starting point is a data base culled from many sources.

In the WELMM approach, only that primary energy extracted and used by the energy transformation systems is taken back to the system boundary of energy in the ground; other inputs are not. Energy analysts would argue that for this reason WELMM is a sub-set of energy analysis, rather than the other way around. The argument is as follows. Taking Figure 5, the WELMM approach does not treat inputs a + b + ... in GER terms but in direct energy terms, and does not count them at all in assessing "primary energy efficiency". Thus, there is a need to do a WELMM on the inputs, and a further WELMM on these inputs. If the numbers are convergent, then the slight error resulting from omission of this treatment is not serious. But there may be occasions upon which the answers are divergent, and one cannot be sure that WELMM will pick that up. If, however, the entire operation is carried out in the form of a dynamic energy model as outlined in Section 3.6, in which all physical inputs are brought back to the same system boundary - the ores in the ground - no inaccuracies are incurred. The WELMM data base can then generate the amounts of steel, cement, water, land, etc. needed to satisfy the energy programme at any point in time. Finding ways of satisfying this need is the task of economic planners, and not energy modellers.

As an instance of the way in which energy analysis can normalise other physical resources than energy, take the case of water. Table 9 lists some approximate numbers for the energy required to deliver 1000 m^3 of fresh water. Since all water is recycled by the atmospheric system and eventually reaches the sea, we can take the desalination of sea-water as the asymptote. It cannot take more energy than 280 GJ/1000 m^3 to make fresh water, and as advances in reverse osmosis are made, that figure will probably fall. With data like this one could formulate from a given country's water resources the energy required for water supply, expressed as volume of water consumed per year, in the form of Figure 9.

Table 9 Energy requirement for water

	Technology Involved	Approximate GER/1000 m^3 GJ
Run-off water in mountainous area	dam	0.2 - 2.0
Purified run-off water	reservoir and plant	2.2
Ground water, 100 m deep	pump	4
Transport in pipelines (1000 miles)	pipelines	60
Transport in ships (1000 miles)	super-tankers	75
Sea water distillation	flash evaporation	280

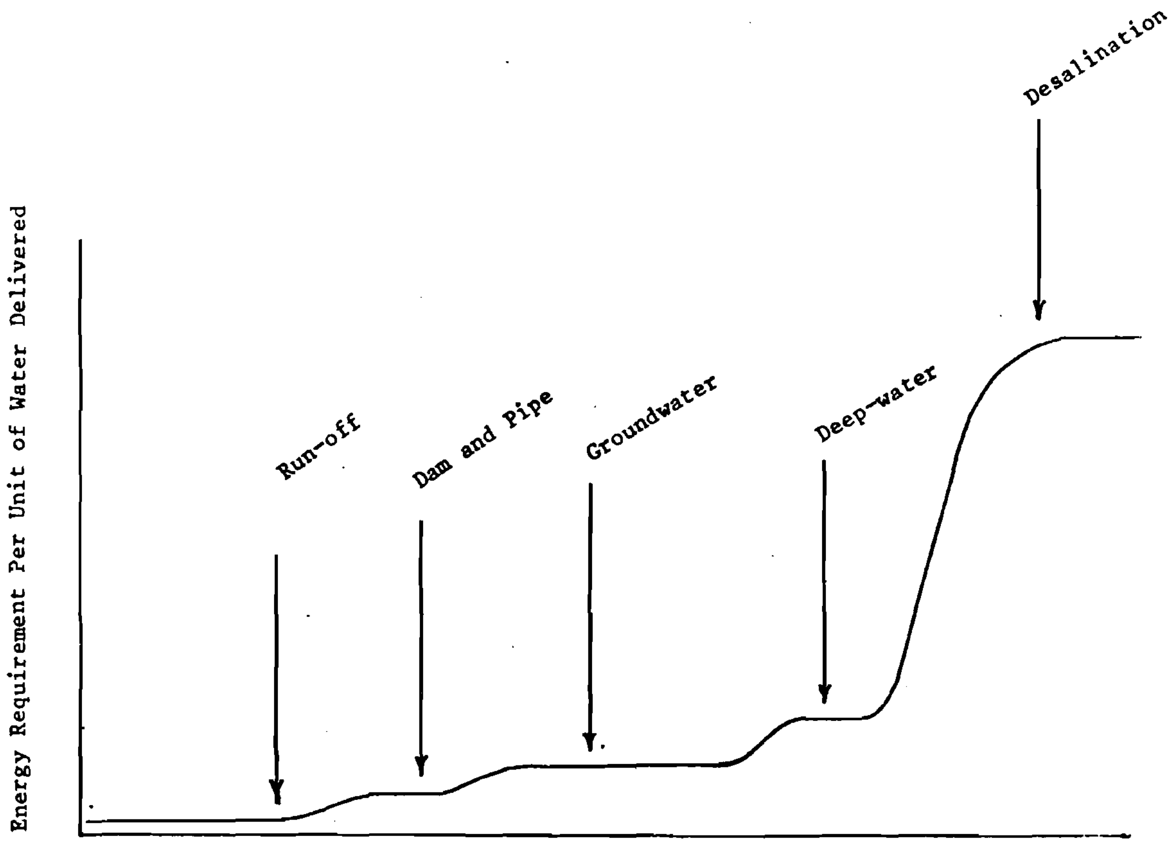

Figure 9 Increase in energy requirements for water supply as consumption grows in a water limited territory.

4.4 Energy Supply Modelling

Many energy supply models are being developed using optimisation techniques. In such models energy demand is set as an exogeneous input, and the model sets out to find the least cost solution to the problem. The model may be a gloval or local model. The principles used are identical. Such models have to make assumptions about the future price of energy resources and technologies. Such prices will be affected by four factors:

(1) inflation;

(2) depletion of resources;

(3) technological improvements in resource extraction;

(4) technological improvements in energy transformation;

(5) political setting of prices (in centrally planned economies).

Inflation is a matter of such consequence, and of so little understanding, that many models avoid it altogether by assuming a world of "constant dollars". This seems a curiously unreal assumption. There is a view, shared by the author that inflation is in fact induced by the decline in resource quality, a point H. Odum /7/ has made with great force.

Then one must ask the question whether the other three factors can be predicted in money terms with any sort of accuracy. Economic projections for any distance ahead are charged with uncertainty, and as was illustrated in Section 3.1 trend extrapolation of technology is risky. What then, the energy analyst asks, is the point of making a sophisticated model, if it is based on a set of crude assumptions?In an article entitled "Theoretical Assumptions and Non-Observed Facts" W. Leontieff /37/ has attacked such model making. He goes on to remark, "True advance can be achieved only through an iterative process in which improved theoretical formulation raises new empirical questions, and the answers to these questions, in their turn, lead to new theoretical insights".

I suggest that energy analysis provides one with a step along the road towards better insights. In the example of the energy supply model, energy analysis can considerably reduce the uncertainty of the price assumptions listed. The coupling of energy analysis with a thorough technological knowledge of the processes of extraction, depletion and energy transformation would enable one to come up with a reliable measure of the future GER for the exploitation of an energy resource, in either enthalpic or free energy terms. These could then be used as a guide to relative prices, thereby reducing considerably the uncertainty in the model.

But inflation remains a problem. Simply by switching to energy as the numeraire in an energy supply model, the problem of handling inflation vanishes.

What emerges? An optimisation model, optimised around minimum free energy use, constrained, as would be the money model, by the perceived constraints, be they political, strategic, environmental and so on. Is that so bad? Are the uncertainties introduced by omitting labour cost from the model such as to invalidate the result? I suggest they are trivial in comparison to the advantages gained. The critic might find it helpful to ponder W.G. Phillips and D.P. Edwards' free energy/price diagram (Figure 4). In passing, one might note that another optimisation model, the original Brookhaven model of K. Hoffman /38/, had one formulation in which it optimised for energy use and produced a result 11% more costly than the money model. It is a pity that this aspect of the Brookhaven model is not more discussed.

4.5 Energy Analysis and Pollution

Technology has today reached a level where it is not too much of an exaggeration to say that any waste stream can be reduced to an acceptable level of pollution, given the will and the investment. It is a straightforward chemical engineering calculation to find the cost or the energy requirement for such an action. But de-pollution necessarily adds to the energy use, and thus in the end of the day to thermal pollution. Energy analysis thus forms an excellent way of internalising the costs of pollution, while at the same time, if incorporated into a model, it can generate waste heat flux diagrams. In a report to OECD /39/ outlining this use of energy analysis for environmental policy, M. Slesser suggested that this could be a way of planning future industrial development in densely populated countries.

5. Some Unresolved Issues in Energy Analysis

5.1 Resources Rendered Economically Inaccessible

The IFIAS convention /1/ defines energy resource use as the amount of resource taken from the ground to furnish a certain need. It ignores the possibility that the extraction process may thereby render some of the resource economically inaccessible. G. Leach /40/ in a trenchant criticism of net energy analysis argues that such is the amount of resource often rendered inaccessible, that to concern oneself with energy

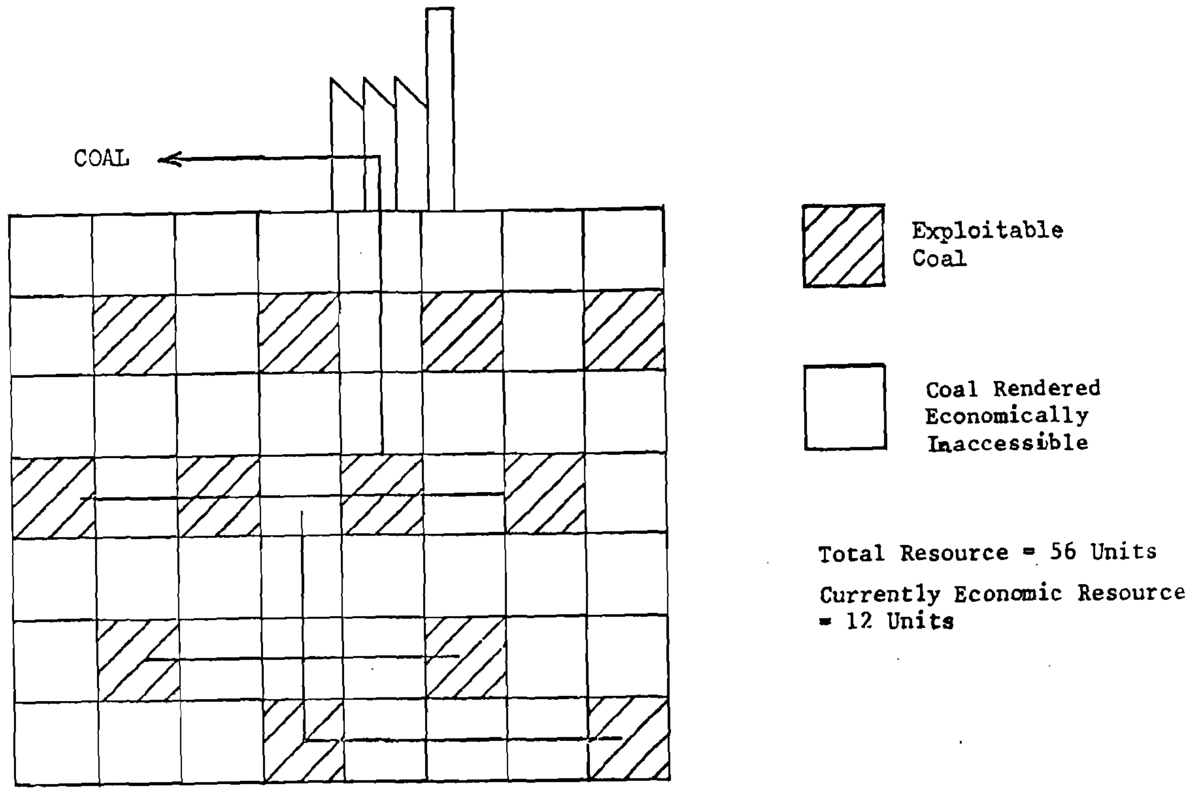

Figure 10 Exploitation leaving economically inaccessible resources

requirement for energy above ground is really irrelevant. M. Slesser /41/ has offered a rebuttal of this criticism pointing out that the interest in net energy analysis is with its economic implication. In fairness to both points of view the reader may care to ponder the following situation.

Figure 10 represents a coal mine containing 56 units of coal. Drilling the shaft and extracting coal can win 12 of those units, but thereby 44 units are rendered inaccessible, except at enormous cost and possibly danger to life.

Let us suppose that to open the mine in the first place an energy investment equal to 2 units was made, and that this has to be amortised over the entire output. Suppose also that each unit of coal extracted required the recycling of 0.05 units of coal for driving machinery etc. Then the anticipated average GER of coal (in MJ/MJ), using the IFIAS convention, would be

$$(2 + .05n + n)/n \quad = \quad \frac{2}{n} + 1.05$$

By the time the twelfth unit has been extracted the average GER has fallen to 1.21[6]. G. Leach argues that one should add to the 2 units of initial investment the 44 units of coal rendered inaccessible. If you do this, he argues, the energy used at the surface to extract the energy (the marginal GER = 1.05) is irrelevant. Figure 11 depicts the outcome.

G. Leach is right, if the point of issue is the loss of energy resources by ill-advised extraction. But if it can be shown that cost is linked to a net energy parameter, then its calculation is undoubtedly interesting. The evidence suggests it is, but, much more research is needed to satisfy criticism

Let us now imagine some time far in the future when energy stocks have become much depleted, and the abandoned coal-mine is re-opened. Perhaps the situation is assisted by the development of new technologies but whether or not, we may expend even more energy recycle to get each unit out, but in the climate of the time it is considered worth it. What do we find? Both the cost, the average GER and the marginal GER have risen. If one was modelling the system, these are the parameters we should require to formulate our model.

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6 Note. The marginal GER is 1.05, and a large difference arises through the enormous investment in the coal mine relative to its potential output.

In my view, Leach's criticism of net energy analysis is based on the misconception that is about stocks, whereas it is really about difficulty of extraction.

5.2 Partitioning

The major unresolved convention in energy analysis is that of partition. Where a process produces more than one economically useful good, how does one partition the input energies against the various outputs? Fortunately in the energy analysis of energy itself, the recommended IFIAS convention serves well. It suggests partition where possible on the enthalpy content of products when those producs are combustible, though free energy would be more appropriate. Outside this, the matter still remains uncertain, though the IFIAS report /1/ does try to deal with it.

5.3 Energy Quality

To an engineer or thermodynamicist energy quality is reflected in an ability to do work. True energy analysis therefore should be conducted in those units - of which Gibbs free energy is possibly the simplest to compute. Even so the task is a hard one. The economist has tried to handle this by ascribing some fairly arbitrary 'qualities' to energy, as in the work of L.L Brookes /42/, and F.G. Adams and P. Miovic /43/. Certainly there are opportunities here for co-operation between the professions. But dimly, one perceives an even more cogent relation, as information theory develops its own paradigm of entropy. There may be some overall inter-relating factor bringing together at last all the factors. The interested reader may care to peruse the works of S. Bagno /44/, M. Tribus /45/, or A.E. Ferdinand /46/.

6. Conclusion

Energy analysis is about estimating the energy resource required to make a given good or service available on the market place, and then interpreting that information within a theoretical framework. The methodology is established, and fairly widely accepted amongst the scientific community if not within the economic community. Differences still exist with respect to system boundary, but these are slowly being resolved.

The application of energy analysis in its simplest form is exactly what engineers have done for a long time with respect to making heat and mass balances. These balances however dealt with fuel use, and not primary energy resource. In this one respect energy analysis, as currently practised may be considered to treat a wider system. The application of the results of energy analysis to simple problems like house heating, estimation of waste, thermodynamic limits represent no new theoretical developments, but have proved useful for a second order 'feel' for economic questions. The future of energy analysis depends very largely on being able to develop a theoretical framework within which the numbers generated by energy analysis methodology can be made to illuminate economic problems. So far only a beginning has been made in this direction. Some possible directions have been indicated in this paper. Certainly there is a need for time series historical studies. What is most important to bear in mind is that with few exceptions energy analysis is neither implicitly supporting nor opposing an energy theory of value.

Reasons have been adduced in this paper to suggest that an energy theory of value by itself would be entirely misleading. A great deal of research needs to be done to establish the utility of energy analysis within economic analysis. My own impression is that it will prove a powerful tool with which to supplement economic analysis, and that as the time horizon moves further and further into the future, energy analysis data will serve as a superior numeraire to money for the estimation of relative prices.

<u>References</u>

(1) Energy Analysis: Conventions and Methodology, Report No. 6, Editor M. Slesser, International Federation of Institutes of Advanced Study, Ulriksdal Slott, S-17171, Solna, Sweden, 1974.

(2) Slesser, M., Dynamic Energy Analysis as a Method for Predicting Energy Requirement, in W.D. Nordhaus, ed., <u>Proceedings of the Workshop on Energy Demand</u>, CP-76-1, International Institute for Applied System Analysis, Laxenburg, Austria.

(3) Webb, A. and D. Peirce, <u>Energy Policy</u>, <u>3</u>, 4 , pp. 318-331 (1975)

(4) Huettner, D.A., The economics of energy analysis, <u>Science</u>, <u>192</u>, 9 April 1976, 101.

(5) Koopmans, T., Workshop on Energy Analysis and Economcis, Lidingö, Sweden, Report No. 9, editor T. Long, IFIAS, June 1975, Ulriksdal Slott, S-17171, Solna, Sweden.

(6) Martino, P., <u>Monetary Physics</u>, a privately published statement, Jusu Jussila, Helsinki, Finland.

(7) Odum, H., <u>Power, Environment and Society</u>, Wiley Inter-Science, New York, 1971.

(8) Hannon, B.M., <u>Annals of the American Academy of Political and Social Science</u>, <u>410</u> (1973), 139.

(9) Thompson, W., British Association for the Advancement of Science, Transactions (A), 527, 1881.

(10) Soddy, F., <u>Wealth, Virtual Wealth and Debt</u>, Allen & Unwin, London, 1926.

(11) Chenery, H.B., Process and Production Functions from Engineering Data, in W.W. Leantief, ed., <u>Studies in Structure of American Economy</u>, O.U.P., London, 1953, 297-321.

(12) Workshop on Net Energy Analysis, Energy Research Centre, Stanford University, Stanford, California, 1976

(13) Berry, S. and M. Fels, Energy costs of an automobile, Bulletin of Atomic Scientists, December 1973, 4.

(14) Slesser, M. Energy subsidy as a criterion in food policy planning, <u>J. Sci. Food & Agriculture</u>, <u>24</u> (1973),1193.

(15) Herendeen, R.A., <u>Energy Input-Output Matrix for the USA 1963</u>, CAC Document 69, Center for Advanced Computation, Urbana, Illinois, USA.

(16) Slesser, M., W. Edwardson , C. Lewis, Energy systems analysis of food production, <u>Food Policy</u>, May (1977) pp. 123-127.

(17) Workshop on Energy Analysis and Economics, Lidingö, Sweden, Report No.9, editor T. Long, IFIAS, June 1975, Ulriksdal Slott, S-17171, Solna, Sweden.

(18) Chapman, P., G. Leach and M. Slesser, The Energy Cost of Fuels, Energy Policy, 2, 3 (1974), 231-244.

(19) Fleming, J.C., Energy Requirements for Ammonia, B.Sc. thesis, 1973, University of Strathclyde, Glasgow, UK

(20) Gyftopolous, E.P. et al., Potential Fuel Effectiveness in Industry, Ballinger, Cambridge, Mass., 1975.

(21) Leathers, J.M., private communication, Dow Chemical Co., 2020 Dow Centre, Midland, Mich. 48640, USA. The company has a vice-president responsible for energy use.

(22) Kreijger, P.C., Energy Analysis of Materials in Building Industry, TNO Conference on Energy Accounting, Rotterdam, February, 1976.

(23) Slesser, M., T. Markus et al., Housing Energy Economics, Report to Scottish Development Department, St. Andrews House, Edinburgh, 1976.

(24) Gardner, E.M. and M.A. Smith, Energy cost of house contruction, Energy Policy, 4, 2 (1976).

(25) Phillips, W.G. and D.P. Edwards, Metal prices as function of ore grade, Resource Policy, 1, 1 (1967), 167

(26) Vogenthaler et al., Net Energy Analysis: An Energy Balance Study of Fossil Fuel Resources, Energy Research Institute of Stae of Colorado, Co., PO Box 366, April, 1976.

(27) Chapman, P. and D. Hemming, Energy Requirement of Some Energy Sources, TNO Conference on Energy Accounting, Rotterdam, February 1976

(28) Leach, G., Energy and Food Production, International Institute for Environment and Development, London, UK, 1975.

(29) Lewis, C., Net Energy of Bio-Mass Systems, Report No. 9, Energy Studies Unit, Strathclyde University, Glasgow, UK,

(30) Rotty, P. et al., Energy Analysis of Nuclear Power, Institute for Energy Analysis, Oak Ridge, Tenn., December 1976.

(31) Gloyne, A.R. and R. Peckham, A Dynamic Net Energy Model of the EEC Energy Transition Programme, Energy Studies Unit, Strathclyde University, Glasgow, UK, 1976.

(32) McLeod, E., Energy Requirements of the Forties Field, Energy Studies Unit, Strathclyde University, Glasgow, UK

(33) Weinberg, A. and H.E. Goeller, The Age of Substitutability, Institute for Energy Analysis, Oak Ridge, Tenn., USA, A Strategy for Resources ed. M. Goldsmith, North-Holland, 1977.

(34) Dunham, K., Non-renewable Mineral Resources, Resources Policy, 1, 1, September 1974, 3-13.

(35) Slesser, M., Energy in the Economy, McMillan, London, 1978.

(36) Grenon, M. and B. Lapillone, The WELMM Approach to Energy Strategies and Options, RR-76-19, International Institute for Applied System Analysis, Laxenburg, 1976.

(37) Leontief, W., Theoretical assumptions and non-observed facts, American Economic Revew, 61, 1, 1971.

(38) Hoffman, K., US Energy System, Dissertation by K. Hoffman, Polytechnic Institute of Brookhaven, N.Y., USA, 1972.

(39) Slesser, M., Energy Analysis as a Tool in the Assessment of Environmental Impact of Energy Production and Use, OECD, Environmental Directorate, Paris, 1975.

(40) Leach, G., Is net energy analysis any use?, Energy Policy, 3, 4 (1975).

(41) Slesser, M., Net Energy Analysis - Critique, Energy Policy, 4, 2 (1976).

(42) Brookes, L.G., More on output elasticity of energy consumption, J. Ind. Economics, 21, November 1972, 83-92.

(43) Adams, F.G. And P. Miovic, On Relative Fuel Efficiency and Ouput Elasticity of Energy Consumption, J. Ind. Economics, 16, 1, 1968.

(44) Bagno, S., The Communication Theory Model and Economics, Transactions, IIIE, 162-181, 19 .

(45) Tribus, M., E.C. McIrvine, Energy and Information, Scientific American, 184, 179-188, 1971.

(46) Ferdinand, L., Theory of System Complexity, Int. J. General Systems, 1, 19-33 (1974).

(47) Lewis, C., Fuels from Biomass - Energy Outlay Versus Energy Returns - A Critical Appraisal, Energy 2, 241, 1977.

(48) Burns, R, ed. J. Kingsley, Tam O'Shanter, R. Burns Poems and Songs, Oxford University Press, London, 1964, 444.

(49) Socolow, R. et al., Energy Conservation Study, Princeton University, 1974, American Physical Society.

(50) Chapman, P., Energy Transport Trends, ERG 014, Open University, Milton Keynes, England, 1977.

(51) Echiburru, R., Energy Analysis of Labour Substitution in Production. M.Sc. Thesis, Strathclyde University, 1977, Glasgow, UK.

APPENDIX 1

AN APOCRYPHAL TALE, AS TOLD BY A SURVIVOR

"Looking back on it, I don't know how the pilot managed. He brought the Boeing 707 in over the atol, and pancaked it in about two metres of water in the lagoon, and slid it on its belly right up to the edge of the sand. We were shaken, but no one was hurt.

We stood around the plane, shocked. What next? Apparently we were miles off the normal air routes, even shipping lanes. The Captain explained that as the radio was out of action, we had best settle down for a long wait.

Two days later we had eaten the last of the food on board. We were hungry. Somebody had managed to open one of the fuel tanks and we had a bonfire of kerosine that night. I think that was what started it. Bill was an engineer, and next morning he got a group of us together and explained his ideas. "Look", he said, "there's one hundred and eighty of us here. That's a lot of people, and I'll bet we've a lot of skills. What else have we got? We've got an atol about eight kilometres by six, we're surrounded by ocean, and we've got 10,000 litres of kerosine in the Boeing's tank. I think it's time we looked after our own survival. We may not be found for months, even years. After all we're supposed to be flying to Alaska. Nobody is going to look for us down here in the Pacific. We've got to set up a community. Grow food, hunt for fish, make ourselves a civilisation."

His words made sense, and later that day, after a foraging party had brought back two turtles and a pile of coconuts, we all sat around the camp fire, lit with a litre or two of kerosine, and talked it over. It turned out we had an agricultural expert, a couple of doctors, three engineers, an economist, the crew, and a whole slate of people who could do civilised things like physiotherapy or chinese carvings, but who had never actually soiled their hands with toil. And toil, Bill said, was what we would have to do to start with. Grow food, and that meant digging in the soil and hauling material to make fences. I remember the moment well. Somebody was making some notes, and complained he couldn't see. So someone threw some more kerosine on the fire. Bill at once was on his feet. "That's fuel, that's energy. All we've got is what lies in the Boeing. Don't waste it. We don't need heat, we got blankets. We don't need light, the sun comes every morning. But we sure as hell need energy to do work for us."

Well most of us didn't understand what he was getting at, but he seemed kind of a clever guy and knew what he was about, so we laid off the kerosine.

Next morning Bill called in a small group of passengers. It seemed they were the practical ones. An electronic engineer, a plumber, a retired carpenter, the radio officer, and what Bill thought best of all, a welder. He explained that we had one whole Boeing. It was ours. Our resource, if you liked. We had a limited amount of kerosine. We had some skills, and we had an island all to ourselves. He explained we had more assets than many people in developing countries had. Why not get our own economy going? Bill explained that the kerosine represented our principal asset, for with it we might do some welding and metal treatment, and eventually generate electricity. But it wouldn't last for ever. "Look" he argued, "we got all the people we need. The problem is not lack of people, its feeding them. What we are limited in is energy. So before that 10,000 litres is finished, we've got to have got a viable community going here. Mac is going to see if he can make some sort of tractor out of one of the engines. Harry here, is going to get a generator for electricity going, and that will enable us to use the radio, and get some music out of that tape recorder we found. Sam, the electronics man, says he thinks we can make some electric motors, and after all we do have the Boeing's batteries, so the plan is to get a small electric car going. But the big deal is to get the solar collector going. Bert, the plumber, will get the job under way. Once he's got us hot water, then we're going to try to make the collector give us work."

"What's work" someone asked, amid laughter.

"It's saving you sweating your guts out. It's having a machine do it for you."

"I like that."

There was a time when I thought we were going to make it. Everything was going so well. Bill used to announce each night how much fuel we had left, and what we still had to achieve, to make ourselves viable. We had managed to rig up an electric engine, for one of the Boeing's inflatable dingies and Harry got the generator going. It seemed to be humming day and night. Night because there was popular demand for light and music. By day to do the jobs. Soon it became popular to use the boat to go over to the far side of the island where the food plantation was instead of walking. Bill objected that it was unnecessary use of energy, but the economist argued that it was the best use of people's time. "After all, Bill" he argued cogently "time is a resource too."

I can't put my finger on just when the scheme broke down. Bill was steadily losing control. People had suddenly found they had political muscle. Why couldn't they have a share of energy? Bill tried to show that though the solar collector was working, the next stage, attaching an engine to it, so that it could start driving the generator and save on kerosine, was a big step, and was going to need some quite massive metal working. "Wait" he pleaded, "till we have the solar engine working. We've got to conserve our resources till we're viable."

"You and your resources" snarled a business man, who had gotten tired of working day in day out in the fields, "what about us? We got a right to a decent standard of living, same as you guys working here on all this crazy machinery. Come on, we'll be rescued soon enough. We might as well live as decently as we can till rescue comes."

Surprisingly it was the economist who backed him up. "Something always turns up" he argued. "Never known it not to."

I guess I survived because I learnt to eat raw fish. By the way, I've used the airline's compensation money to buy a real good solar engine. Even fuels the electric car I use to get to town."

APPENDIX 2 Energy Analysis Example: Energy analysis of ammonia production

Source: Vancini C.A., Synthesis of Ammonia, McMillan, London, 1971, p. 281.

This process is an air/methane process for a large (300,000 t/yr) plant, with efficient energy use. Heat requirements are met largely by the exothermicity of the reaction. The main internal energy use is for electrically driven compressors for gas pumping to high pressure. Other processes use gas driven compressors.

Key Inputs for 1 t Ammonia as Solution	Fuel	(GJ)GER
Feed-stock natural gas 538 m^3	21.3 GJ	22.16
Fuel natural gas	8.1 GJ	8.44
Power 890-950 HP on 800 t/day plant	20 kWh[1]	.28
Water 250 m^3 (see Table 4.3.1; ground water)		1.0
Capital $ 110 x 10^6 (1976) amortised over 15 years		2.93
Total		34.81, say 35

GER Ammonia = 35 MJ/kg

1976, Uk, Braun process

[1] typical US, UK electricity GER, lower in most European countries.

APPENDIX 3

ABBREVIATIONS

ERE	-	Energy Requirement for Energy usually expressed as MJ energy resource used per MJ fuel delivered
ETS	-	Energy Transformation System The system by which in-ground resources are turned into fuels
GER	-	Gross Energy Requirement the energy resource, expressed in terms of enthalpy of combustion to deliver a good or/service
IFIAS	-	International Federation of Institutes of Advanced Study
SESU	-	Strathclyde University convention on net energy
WELMM	-	I I A S A program an energy resources entitled Water, Energy, Land, Mateirals and Manpower.